Plasma Assisted Ignition and High-Speed Flow Control: Non-Thermal and Thermal Effects

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Outline

I. Low-Temperature Plasma Assisted Ignition:

Demonstrating non-thermal plasma chemical ignition mechanism in uniform, repetitively pulsed, nanosecond pulse discharges

II. High-Speed Flow Control by Plasmas:

Using repetitively pulsed localized heating to excite flow instabilities, for mixing enhancement and noise reduction

Background:
Nonequilibrium plasma assisted combustion (PAC)

- **Plasma assisted ignition and combustion studied using different types of discharges: spark, MW, RF, pulsed corona, nanosecond pulse, etc.**
- **Ignition delay time in non-flowing, shock-preheated H_2-air and C_xH_y-air mixtures reduced by a single-pulse, nanosecond duration fast ionization wave discharge (Starikovskii et al, 2003-05)**
- **Repetitively pulsed nanosecond duration plasmas stabilize lean premixed propane-air flames, increase flame blow-off velocity, expand the flammability limits (Starikovskii et al, Laux et al, Cappelli et al, 2003-06)**
- **Filamentary pulsed corona discharge (~ 100 ns) : ignition delay time reduced compared to spark plug ignition at the same pulse energy (Gundersen et al., 2003-05)**
- **Nanosecond repetitively pulsed plasmas: flow ignition, combustion, and flameholding achieved at plasma temperatures 300-400^0 C below autoignition temperature (Ohio State, 2003-07)**

Interpretation of PAC experiments: two opposing viewpoints

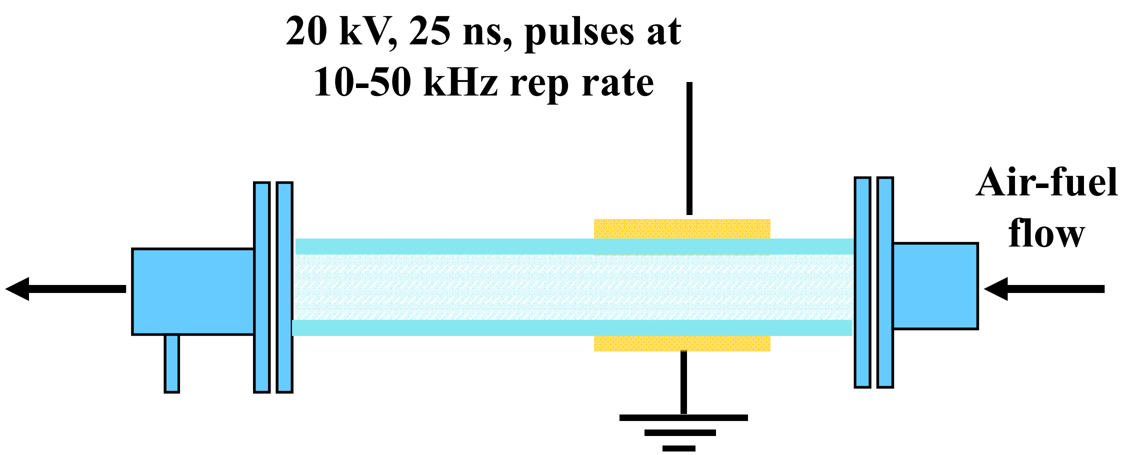
- **Thermal:** Ignition due to rapid localized heating by the plasma (due to filamentation and arcing)

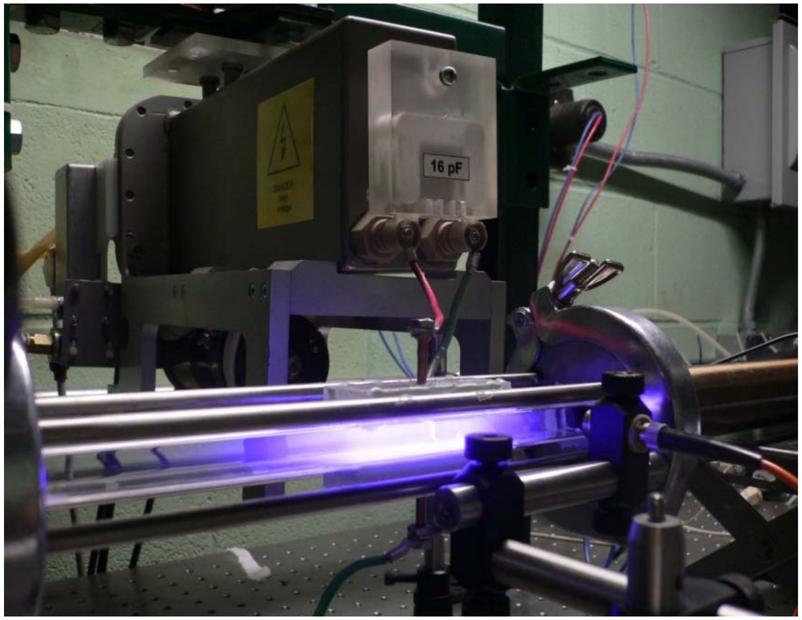
- **Non-thermal:** Ignition due to radical generation by the plasma (O, H, OH, C_xH_y, etc.), which provides key radical initiation step at low temperatures

Isolating and demonstrating possible non-thermal ignition mechanism has been difficult. To do this, we need to:

  - Identify a "test bed" experiment suitable for this purpose
  - Minimize plasma non-uniformity and localized heating
  - Measure key radical species number densities and ignition delay time
  - Demonstrate kinetic mechanism of plasma assisted ignition in kinetic modeling calculations
  - Compare modeling calculations with experiment

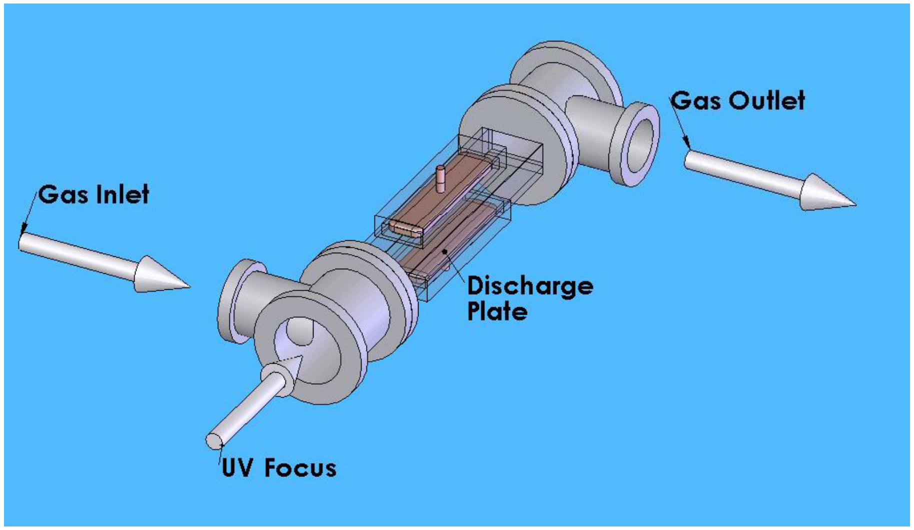
Flow ignition /flameholding in a repetitively pulsed nanosecond discharge (AIAA 2008-1106)

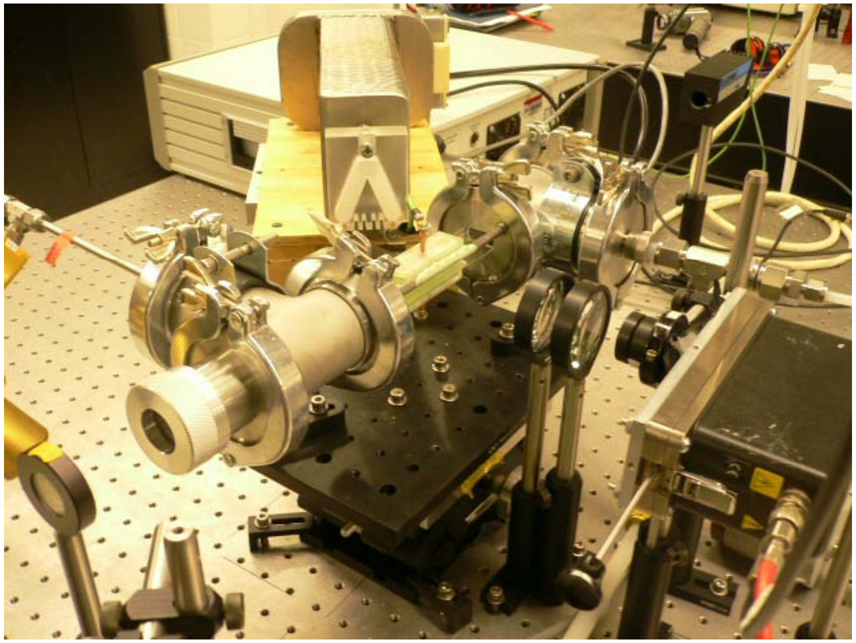




- Steady state flow experiments
- Premixed ethylene-air flows, u= 3-10 m/sec
- Ignition, flameholding, and steady combustion at ν>40 kHz
- Kinetic modeling in good agreement with experiment
- Not suitable for quantitative, predictive ignition kinetics studies: non-uniform axial temperature distribution, possible flame flashback / blowoff / reignition; convection and conduction heat transfer

TALIF O atom density measurements in a single-pulse nanosecond discharge (AIAA 2008-1110)





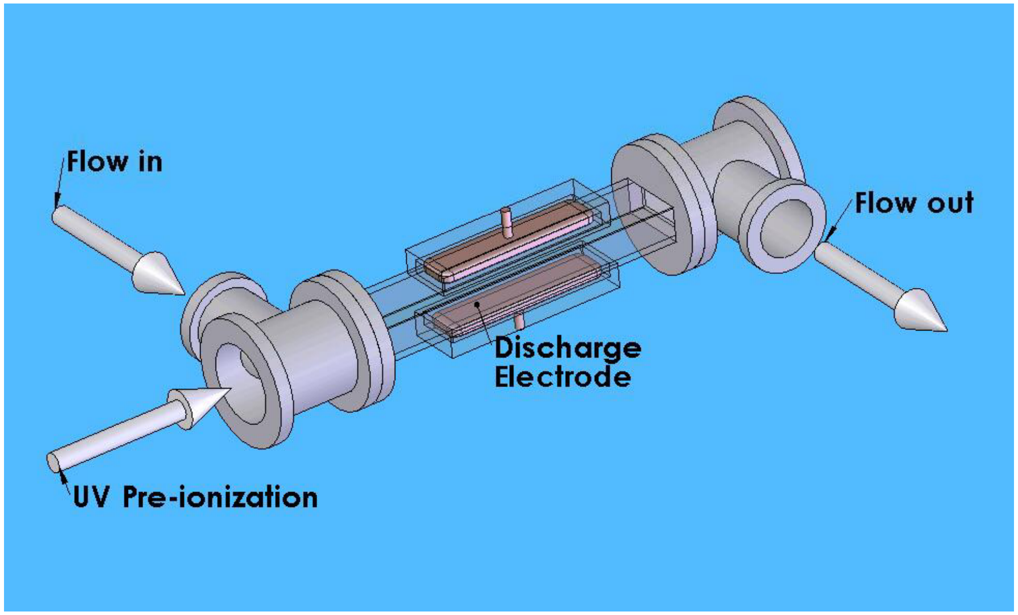
- Single-pulse discharge experiments (ν=10 Hz, u<1 m/sec) in air, methane-air, and ethylene-air
- Stable uniform plasma with no sign of filament formation
- O atom concentration measured as a function of time after the pulse
- Kinetic modeling in good agreement with experiment
- Can be used for "batch" (slow flow) ignition studies using a high rep rate pulse burst: flow / convection heat transfer effects can be neglected

Objectives / Motivation

- **Measure "batch" pulse burst ignition delay time in slow, premixed air-fuel flows at conditions where plasma can be characterized**
- **Compare with kinetic model predictions**
- **Identify kinetic mechanism of plasma assisted ignition at low temperatures**

- **Insight into fundamental kinetic mechanism of low-temperature plasma ignition**
- **Development of efficient nonequilibrium plasma igniters for internal combustion and jet engines: confident ignition in a wide range of equivalence ratios, pressures, and flow velocities; high-altitude relight**

Experiment Schematic



Flow / discharge geometry:
quartz channel 22 x 10 mm cross section, 14 x 63 mm electrode plates

Flow velocity 80 cm/sec, residence time in discharge ~80 msec (w/o plasma)

Pulse burst:
Up to 1000 20 kV, 25 ns pulses at ν=10-50 kHz, pulse energy ~1 mJ/pulse

Pre-ionization:
UV lamp (to achieve breakdown on the first pulse)

Diagnostics:
gated ICCD camera images (broadband), emission spectra (OMA), time-resolved emission (PMT/monochromator)

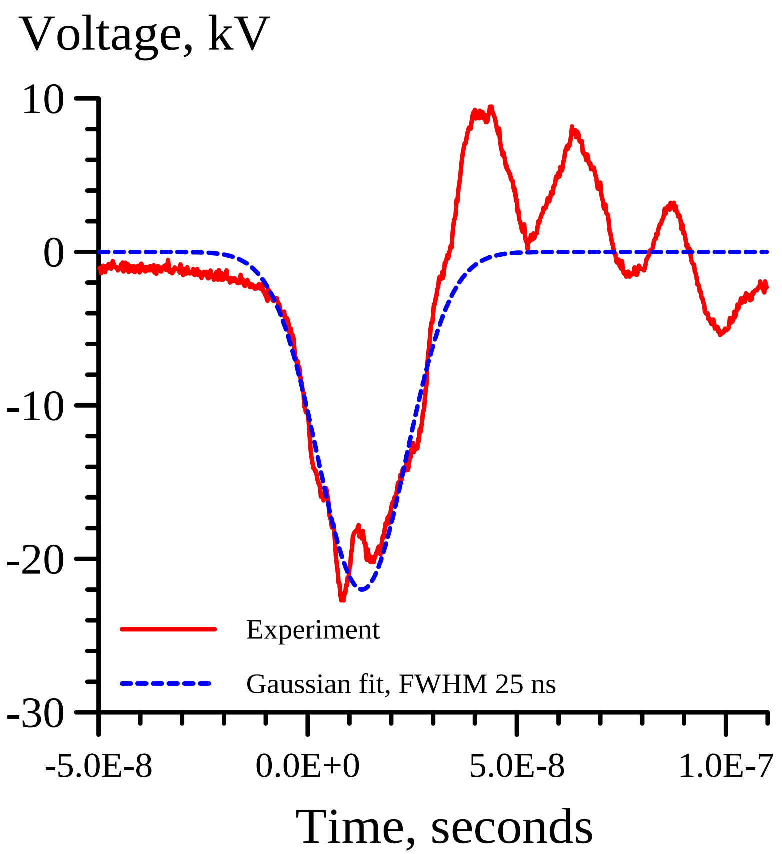
Need to know:

Whether plasma is uniform

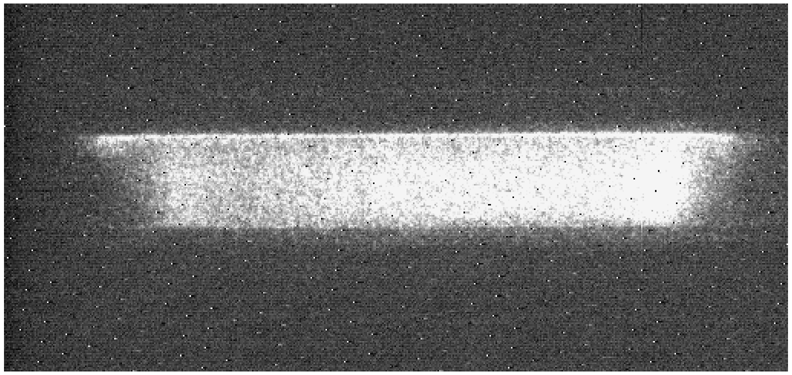
Pulse energy coupled to flow

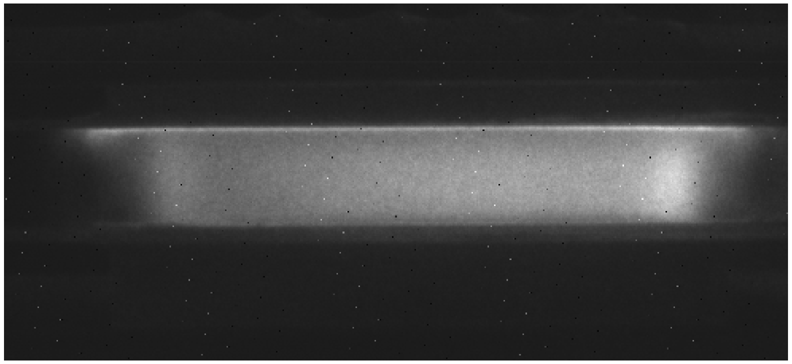
Pulse energy variation during burst

Typical voltage pulse shape and broadband plasma images



20 kV peak voltage, FWHM 25 nsec

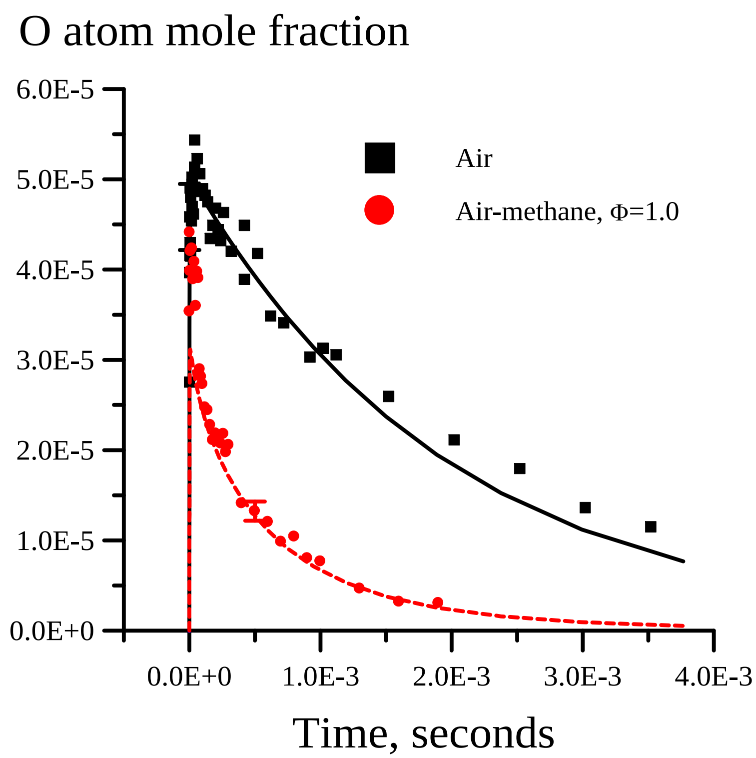


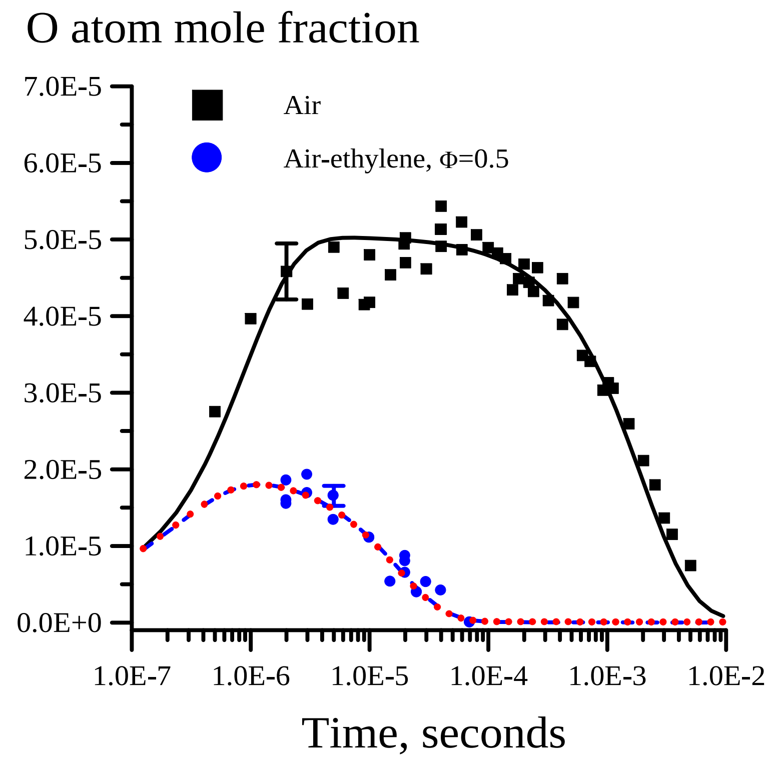


Gated ICCD camera images (300 ns gate). Nitrogen, P=60 torr, ν=5 kHz. Top, single pulse; bottom, 100 pulse average.

Uniform plasma in both cases

Pulse energy inference: TALIF O atom density measurements in a single pulse discharge (AIAA 2008-1110)





- **Pulse energy measured by integrating voltage and current waveforms: ≈1 mJ/pulse. Large uncertainty due to large forward and reflected powers (several mJ/pulse)**
- **Pulse energy inferred from peak O atom density in air using kinetic model of air plasma: 0.76 mJ at E/N=250 Td; in good agreement with pulsed discharge model (0.7 mJ)**
- **Excellent agreement with measured absolute time-dependent O atom concentrations (for same pulsed energy in air and fuel-air mixtures)**

Electric field during the pulse: inferred from ratio of N_2(C→B) and N_2^+(B→X) emission

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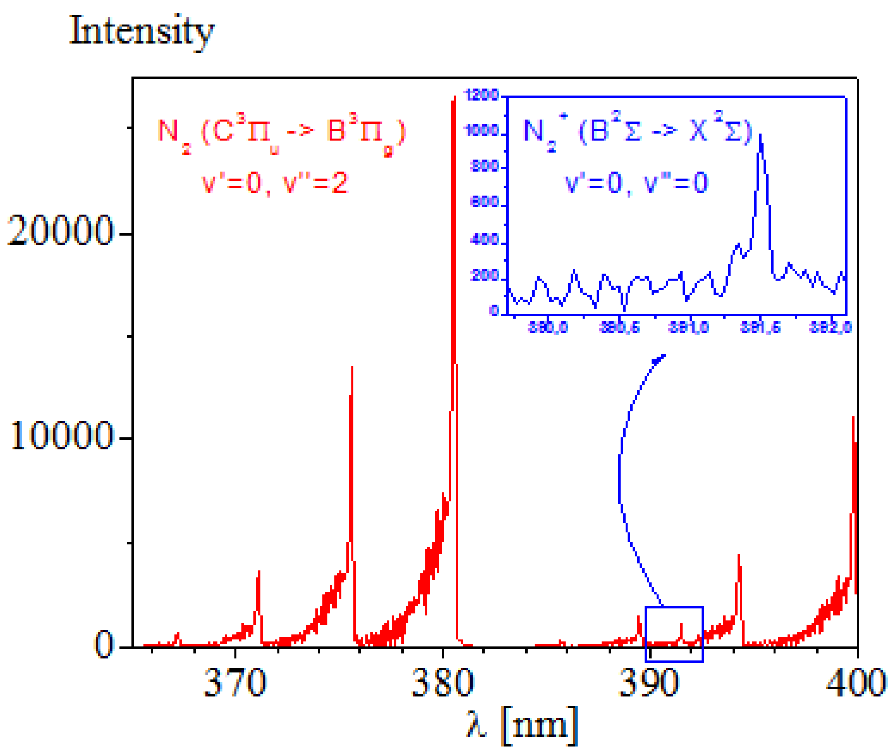

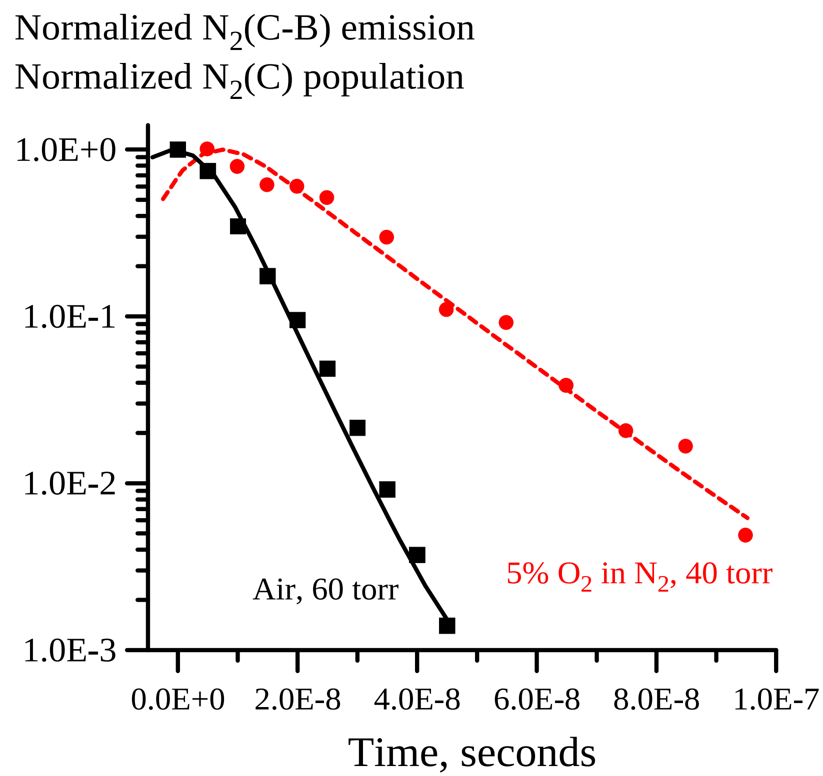

- **Emission decays within ~10 nsec, i.e. signal collected during the pulses**
- **Collisional and radiative lifetimes & Franck-Condon coefficients taken from literature**
- **Inferred E/N = 330 ± 30 Td in good agreement with pulsed discharge model (E/N≈360 Td)**
- **Experimental demonstration of gap shielding (U_{peak}/L≈1000 Td)**

Hydrocarbon-air plasma chemistry kinetic model
(to predict ignition delay time)

- **Air plasma model: equations for ground state neutral species (N, N_2, O, O_2, O_3, NO, NO_2, N_2O), charged species (electrons and ions), and excited species ($N_2(A^3\Sigma)$, $N_2(B^3\Pi)$, $N_2(C^3\Pi)$, $N_2(a'^1\Sigma)$, $O_2(a^1\Delta)$, $O_2(b^1\Sigma)$, $O_2(c^1\Sigma)$, $N(^2D)$, $N(^2P)$, $O(^1D)$) produced in the plasma.**
- **Two-term expansion Boltzmann equation for plasma electrons**
- **Quasi-1-D flow equations; conduction heat transfer (HT time ~ 10 msec)**
- **Fuel-air plasma: model combined with GRI Mech 3.0 or with USC (Wang et al., better C_2 chemistry) C_xH_y oxidation mechanisms, supplemented with fuel dissociation by electron impact and in reactions with electronically excited nitrogen**
- **Peak E/N adjusted to fit O atom density measured in a single pulse discharge in air to match inferred pulse energy, 0.76 mJ/pulse**
- **Pulse energy kept the same in air and air-fuel mixtures**
- **Validated by comparison with time-dependent O atom density measured in single pulse discharges in air, CH_4-air, and C_2H_4-air (AIAA 2008-1110)**

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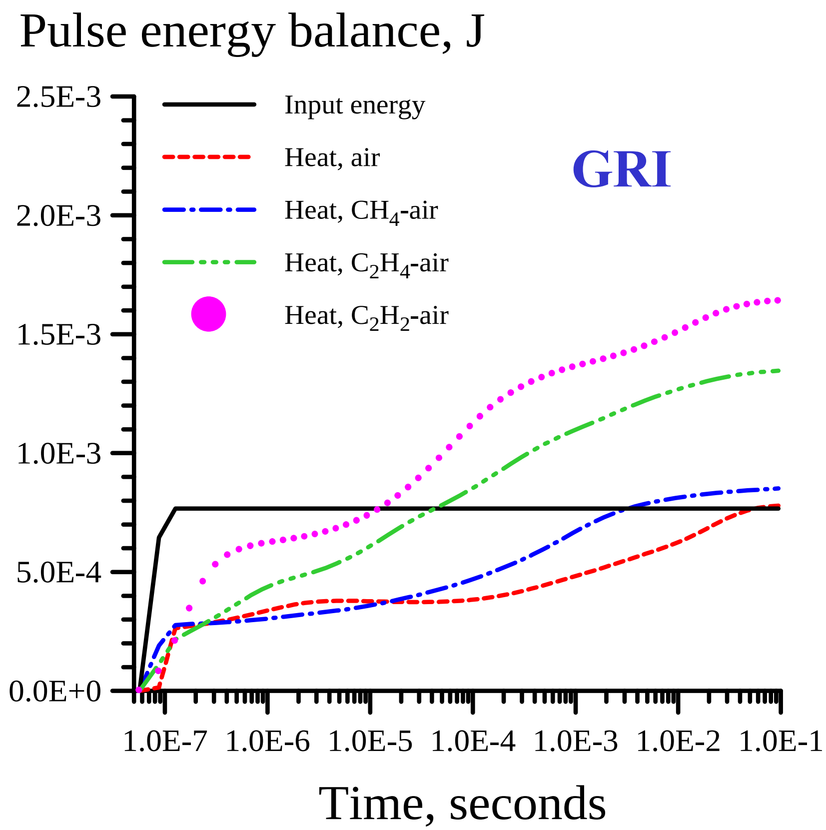
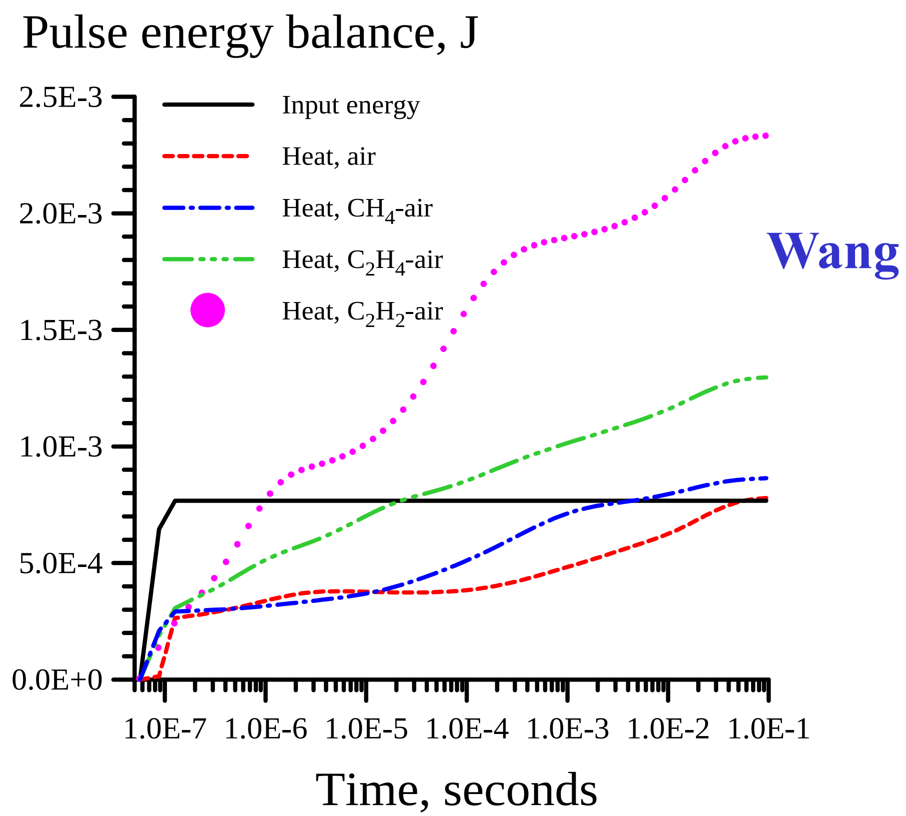
Kinetic modeling: additional heat release by plasma chemical reactions





- **Significant additional energy release from fuel species reacting with radicals produced by the plasma (O, H, OH, and C_xH_y) in ethylene-air (70-80%) and especially acetylene-air (a factor of 2 to 3)**
- **Much less pronounced in methane-air (10-15%)**
- **Suggests shorter ignition times in acetylene, longer in ethylene, and longest in methane**

Dominant radical generation / loss and energy release processes in air and ethylene-air

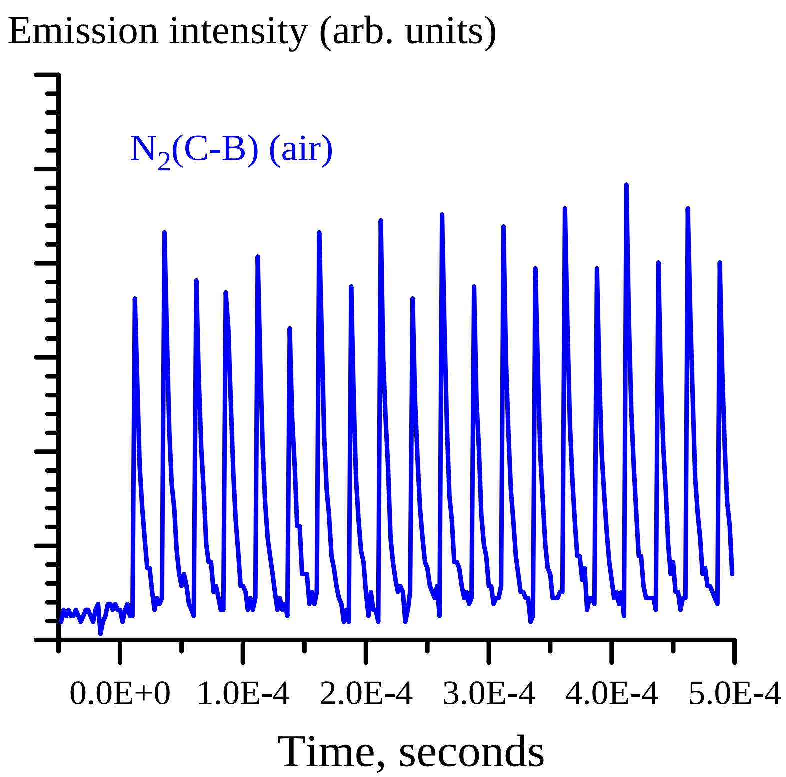
O atom generation
$N_2 + e^- = N_2(A^3\Sigma) + e^-$
$N_2 + e^- = N_2(B^3\Pi) + e^-$
$N_2 + e^- = N_2(C^3\Pi) + e^-$
$N_2 + e^- = N_2(a'^1\Sigma) + e^-$
$O_2 + e^- = O(^3P) + O(^3P,^1D) + e^-$
$N_2(C^3\Pi) + O_2 = N_2(a'^1\Sigma) + O_2$
$N_2(a'^1\Sigma) + O_2 = N_2(B^3\Pi) + O_2$
$N_2(B^3\Pi) + O_2 = N_2(A^3\Sigma) + O_2$
$N_2(A^3\Sigma) + O_2 = N_2 + O + O$
O atom decay
$O + O_2 + M = O_3 + M$
$O + O_3 = O_2 + O_2$

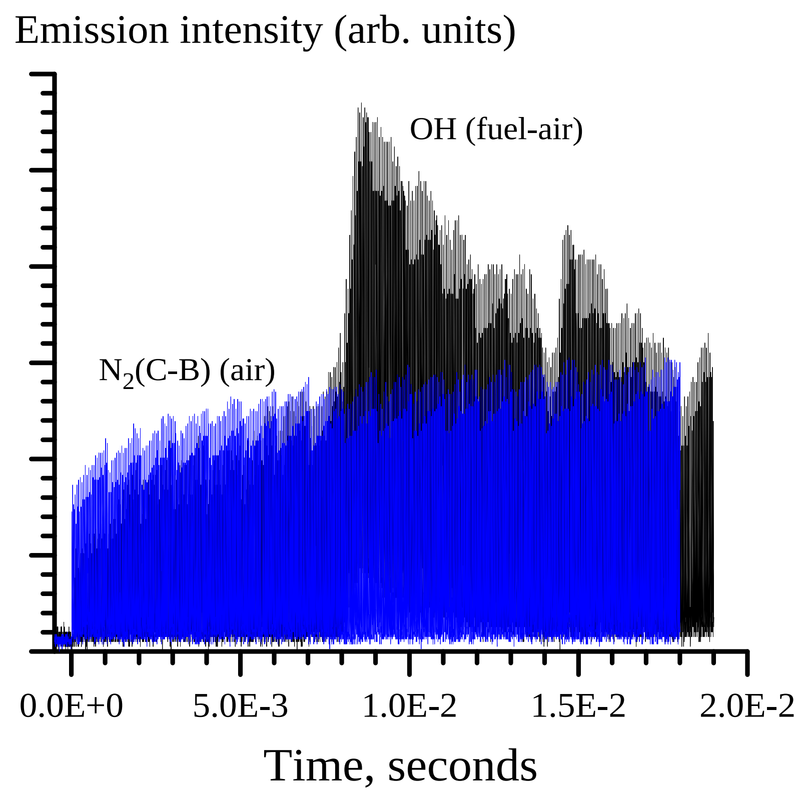
Is plasma just a fancy heater?

Is that all there is to it?

Fuel dissociation
C_2H_4 + e- = products + e-
$N_2(A^3\Sigma) + C_2H_4 = N_2 + C_2H_3 + H$
$N_2(B^3\Pi) + C_2H_4 = N_2 + C_2H_3 + H$
$N_2(C^3\Pi) + C_2H_4 = N_2 + C_2H_3 + H$
$N_2(a'^1\Sigma) + C_2H_4 = N_2 + C_2H_3 + H$
O atom decay
$O + C_2H_4 = CH_3 + HCO$
$O + C_2H_4 = H + CH_2CHO$
$C_2H_3 + O_2 = HCO + CH_2O$
$C_2H_3 + O_2 = O + CH_2CHO$
Energy release
$O + CH_2CHO = H + CH_2 + CO_2$
$H + O_2 + M = HO_2 + M$
$O + HO_2 = OH + O_2$
$OH + HO_2 = O_2 + H_2O$
$OH + C_2H_4 = C_2H_3 + H_2O$
$HO_2 + CH_3 = OH + CH_3O$
$CH_3O + O_2 = HO_2 + CH_2O$
$O_2 + CH_2CHO = OH + HCO + HCO$
$HCO + O_2 = HO_2 + CO$
$HO_2 + HO_2 = O_2 + H_2O_2$
$CH_2 + O_2 = H + H + CO_2$

Pulse burst discharge emission in air and ethylene-air (P=60 torr, φ=1, ν=40 kHz, 308 nm)





- **Air (higher time resolution)**
- **N_2(C→B) emission spikes unresolved**
- **Peak emission appear to oscillate due to low number of points across the peak**

- **Air and C_2H_4-air (lower time resolution)**
- **N_2(C→B) emission steady in time**
- **Emission overshoot in ethylene-air after ~360 pulses (~9 msec): OH(A→X)**
- **Overshoot reproduced well run-to-run**

Pulse burst discharge emission in ethylene-air (P=60 torr, φ=1, ν=40 kHz, 308 and 563 nm)

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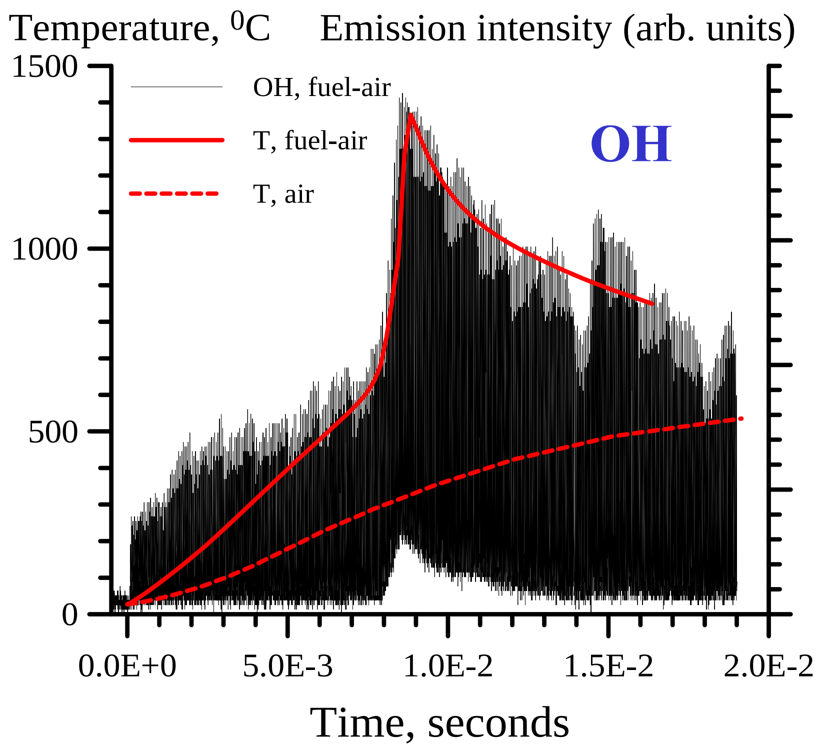

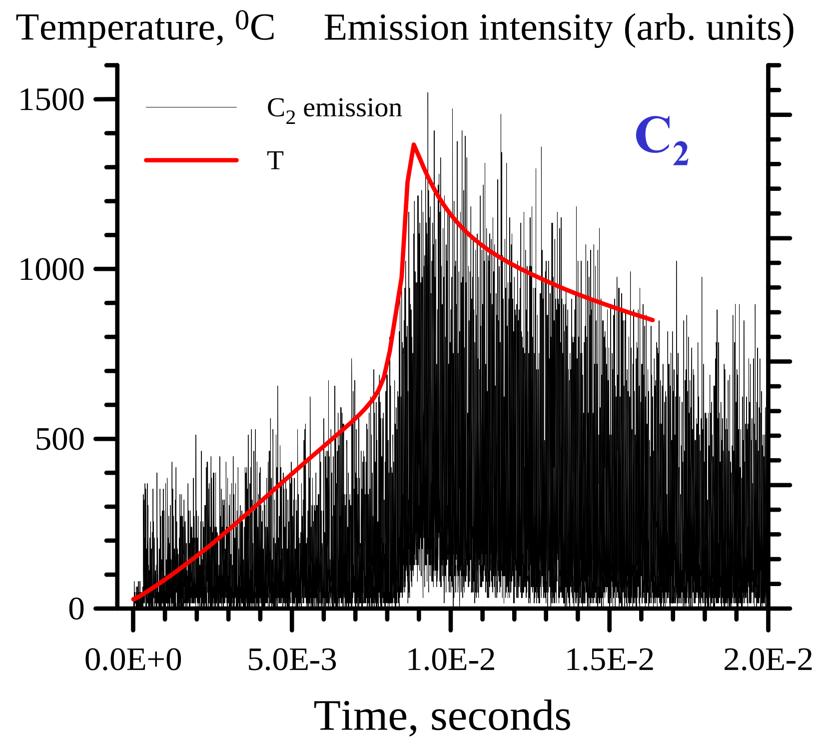

- **Both traces show emission intensity overshoot after ~360 pulses (~9 msec)**
- **Both traces show emission "footprint" at ~9 msec: emission no longer goes down to zero between pulses, indicating self-sustained emission process during combustion (OH and C_2 Swan)**
- **Emission overshoot timing in good agreement with temperature and OH concentration peaks predicted by the kinetic model**

Pulse burst discharge emission in ethylene-air (P=60 torr, φ=1, ν=40 kHz, 431 and 457 nm)

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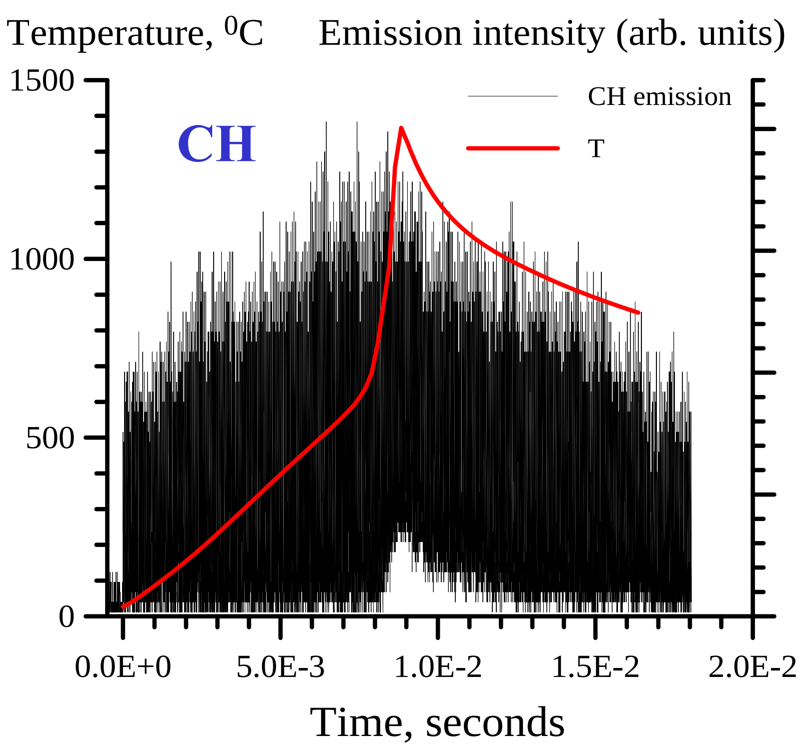

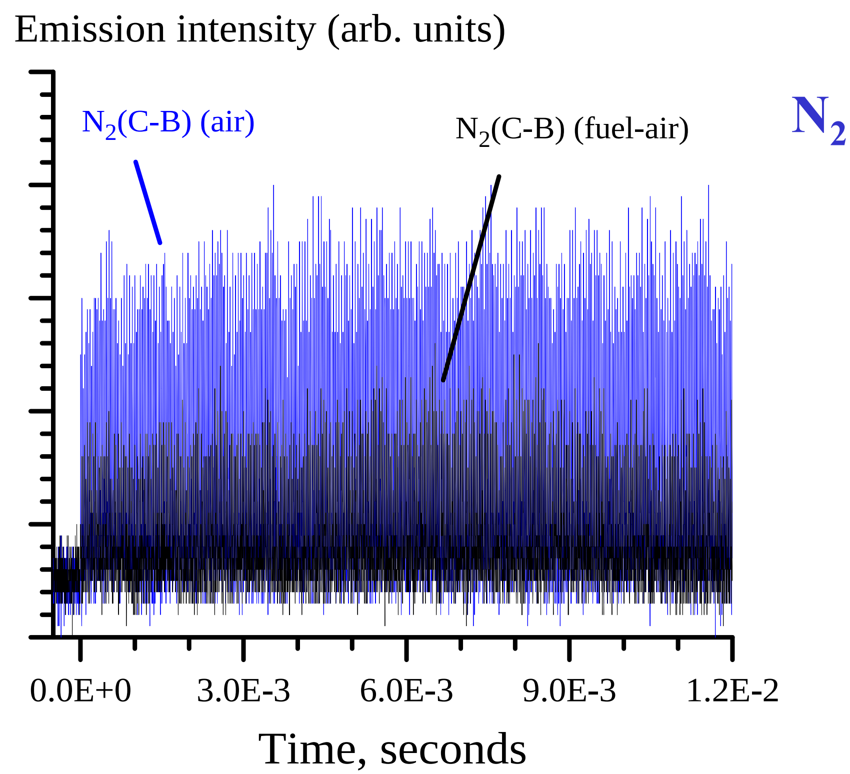

- 431 nm emission shows (CH) emission "footprint" at ~9 msec, which coincides with OH and C_2 emission "footprints" and temperature peak predicted by the model
- No N_2(C→B) emission overshoot detected for bands not overlapping with strong OH, CH, and C_2 bands (e.g. 457 nm)

Summary: Emission "footprints" are due to ignition in test section

Kinetic model predicts ethylene ignition delay time at baseline conditions accurately

Experimental and calculated ignition delay times
(ethylene and acetylene at P=60 torr, GRI 3.0)

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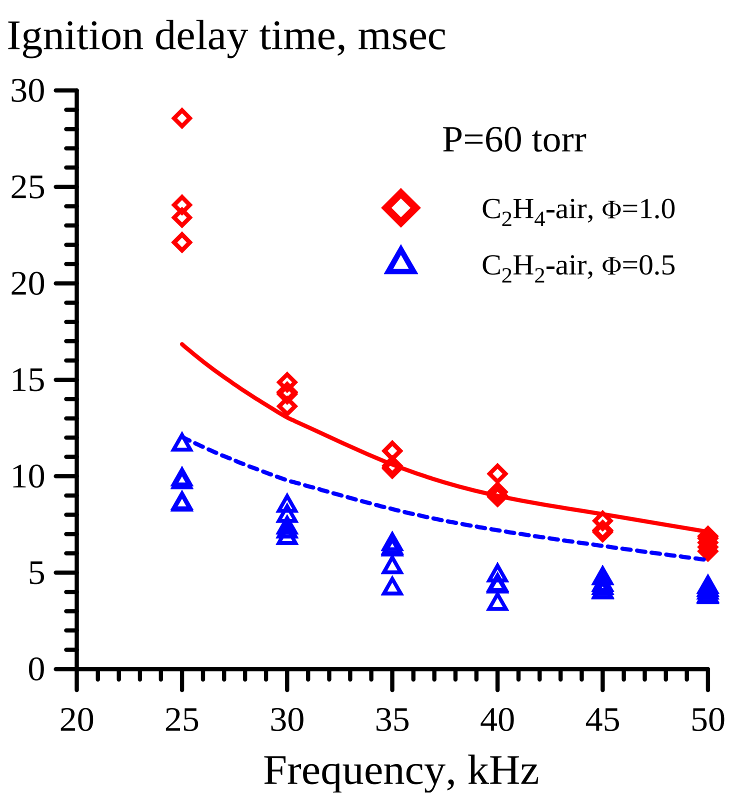
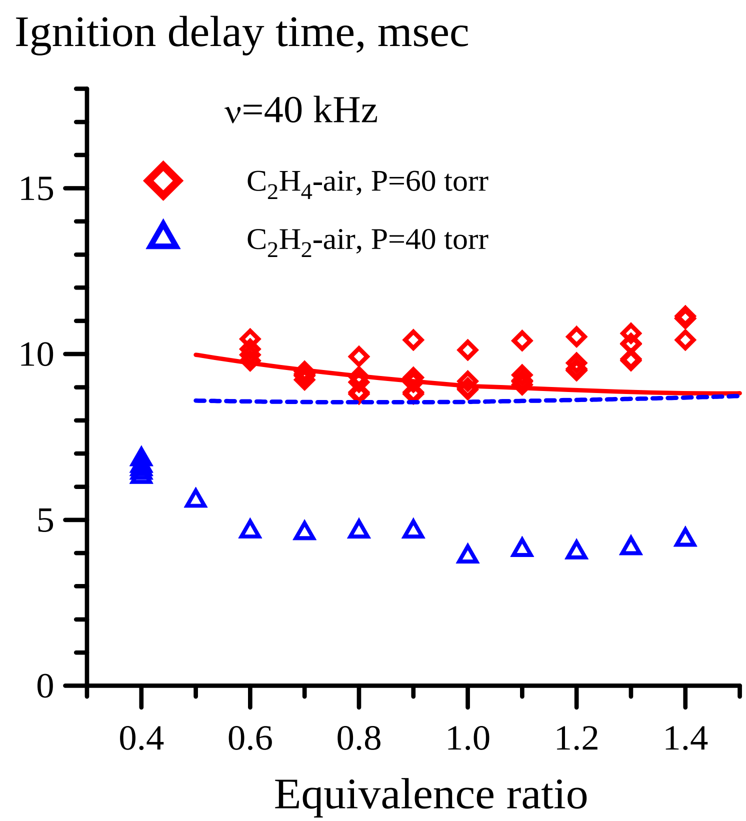
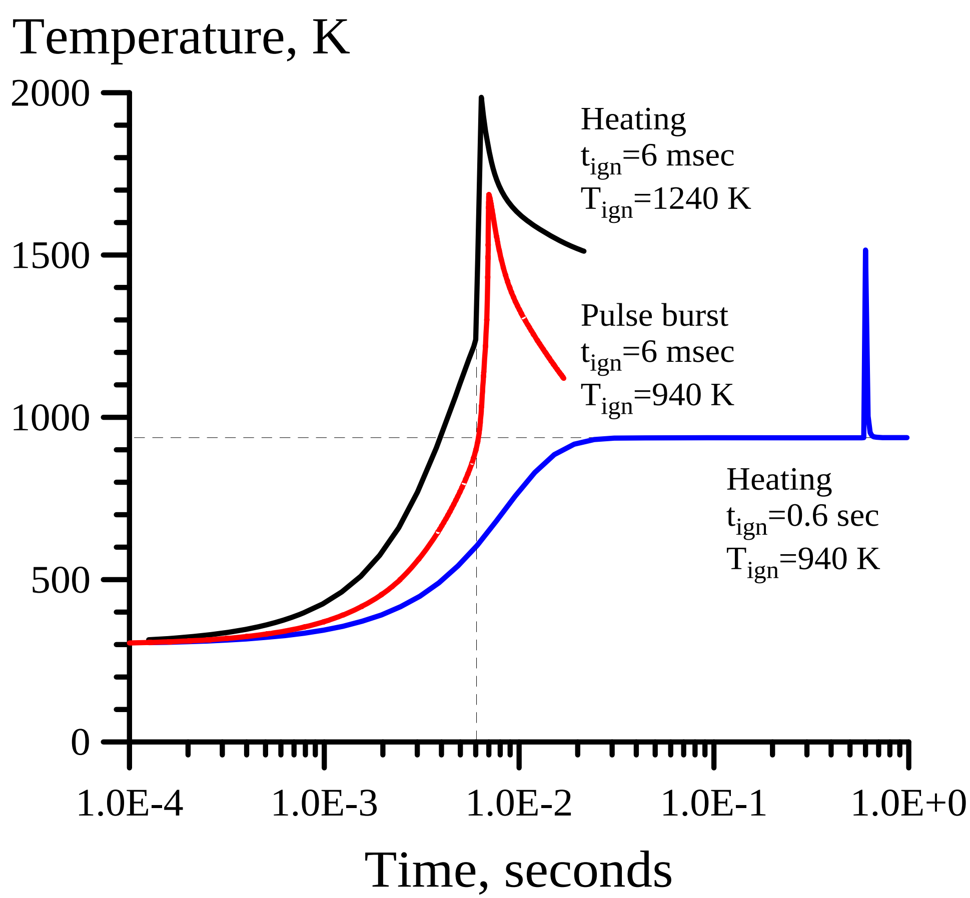




- **Very good run-to-run reproducibility (10-20%)**
- **Excellent agreement for ethylene-air (except at 20 kHz; likely convective cooling effect)**
- **Model predicts longer ignition delay time in acetylene-air (by up to 50-100%)**
- **Measured and predicted ignition delay decreases with rep rate, nearly independent of φ**
- **Both experiment and model predict no methane ignition in the entire range of conditions**

Kinetic modeling: is ignition a thermal effect?

Pulse burst ignition vs. equilibrium heating (ethylene-air, P=60 torr, φ=1, ν=50 kHz)



Case I (black curve): heating rate adjusted to produce same ignition delay time as during pulse burst ignition

Plasma ignition temperature lower by 300^0 C (due to chain reaction acceleration by radicals)

Case II (blue curve): heating rate adjusted to produce same ignition temperature as during pulse burst ignition

Plasma ignition delay time shorter by 2 orders of magnitude (due to chain reaction acceleration by radicals)

Kinetic modeling: comparison of two C_xH_y oxidation mechanisms, GRI 3.0 and Wang (P=60 torr, φ=1, ν=50 kHz)

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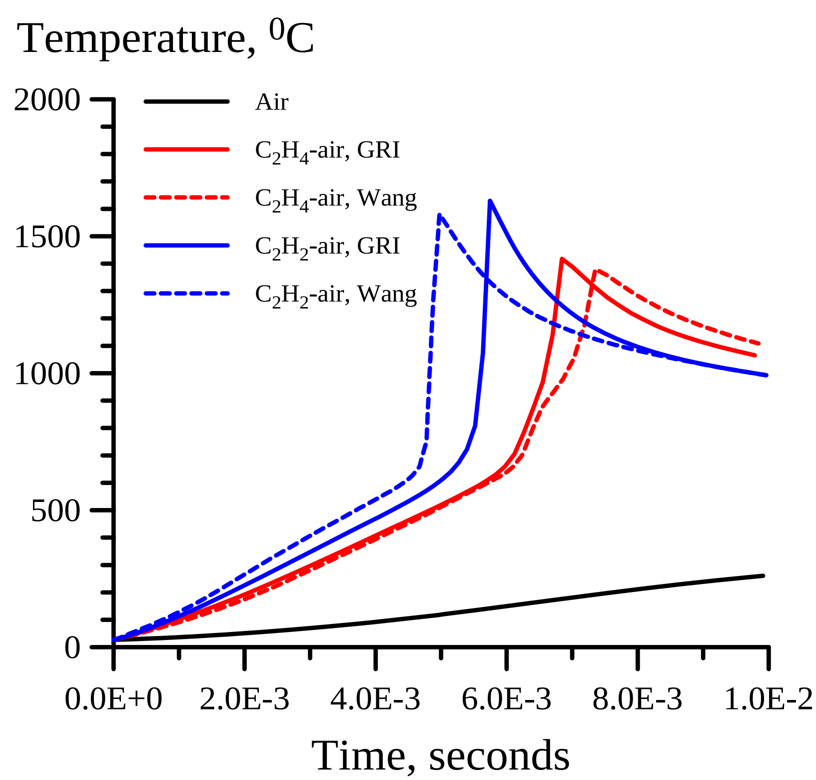
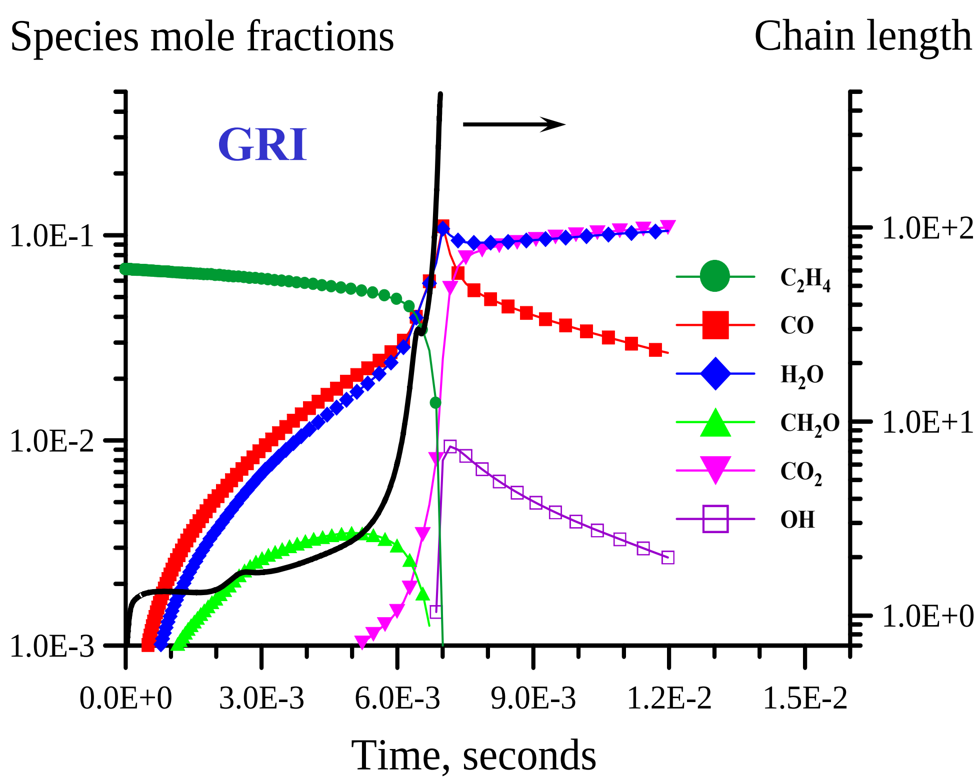




- **Both mechanisms predict ignition delays, temperatures, and species concentrations in ethylene-air and acetylene-air close to each other**
- **Reaction chain length greatly increases as the temperature rises**
- **Temperature and OH concentration overshoots occur at the same time**
- **Both mechanisms predict no methane-air ignition at the present conditions (no additional plasma chemical energy release + rapid heat transfer to the walls): consistent with experiment**

Summary: Plasma Assisted Ignition

- **Ignition delay time measured in premixed methane-air, ethylene-air and acetylene-air flows excited by nanosecond pulse burst, uniform, low-temperature plasma**
- **Kinetic model of hydrocarbon-air plasma chemistry model developed**
- **Pulse energy used by the plasma chemistry model (0.76 mJ/pulse), inferred from TALIF O atom measurements, in good agreement with prediction of nanosecond pulse discharge model (0.7 mJ/pulse)**
- **Both electric field measurements (330 ± 30 Td) and nanosecond pulse discharge model predictions (360 Td) demonstrate strong plasma shielding by charging dielectrics**
- **Both experiment and model demonstrate absence of ignition in methane-air mixtures**
- **Experimental ignition delay time in ethylene-air in very good agreement with kinetic model of nanosecond pulse hydrocarbon-air plasmas**
- **Predicted ignition delay time in acetylene-air 50-100% longer than in experiment: acetylene-air plasma chemistry model may well be oversimplified**
- **Kinetic mechanism of nanosecond plasma ignition (additional heat release in fuel reactions with plasma-generated radicals + chain reaction acceleration by radicals) has been identified with confidence**

On-going and Future Work

- **Direct measurements of pulse energy vs. pulse number and pulse rep rate (by integrating voltage and current wave forms): does the pulse energy remain the same during the burst?**
- **ICCD camera flame imaging at different moments of time: demonstrate that ignition indeed occurs in a large volume**
- **Pulse burst ignition delay time measurements in a wide range of pressures: can non-thermal, large volume ignition be achieved at high pressures?**
- **Spatially- and time-dependent temperature measurements (CARS): does the temperature increase at the same rate at different locations?**

- **Other key radical species measurements: H atoms (TALIF) and OH (LIF)**

Background: Two Basic Mechanisms of Plasma Flow Control (without magnetic field)

EHD

- Coulomb force interaction in DBD discharges (Roth et al, Corke et al, Artana et al, Starikovskii et al, Moreau et al): boundary layer flow separation control, P~ 1 atm, u_∞~10 m/s. Strong indication that dominant effect of DBD plasma at higher velocities is thermal.

Heating

- Bulk flow heating by glow discharge (Mishin et al., Klimov et al.): shock weakening and drag reduction, P~0.1 atm, u_∞~1 km/s. High power budget, not scalable to high pressures and flow dimensions.
- Localized flow heating by pulsed lasers and arc discharges (Myrabo et al, Tretyakov et al, Elliott et al, Leonov et al): P~0.5 atm, u_∞~500 m/s, high power budget (up to ~10 kW)
- Targeting flow instabilities by repetitively pulsed localized arc filament plasmas: heating at the right place at the right frequency

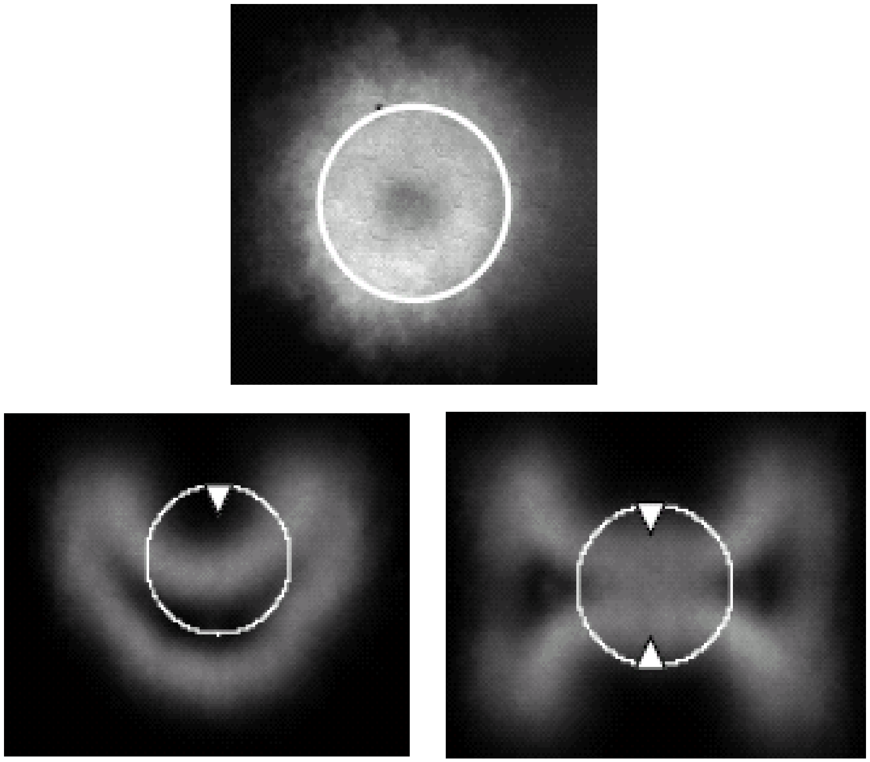
Motivation

- Develop energy-efficient arrays of plasma actuators for high-speed flow control, scalable to large flow dimensions
- Applications for mixing enhancement and noise reduction in jet engines

Objectives

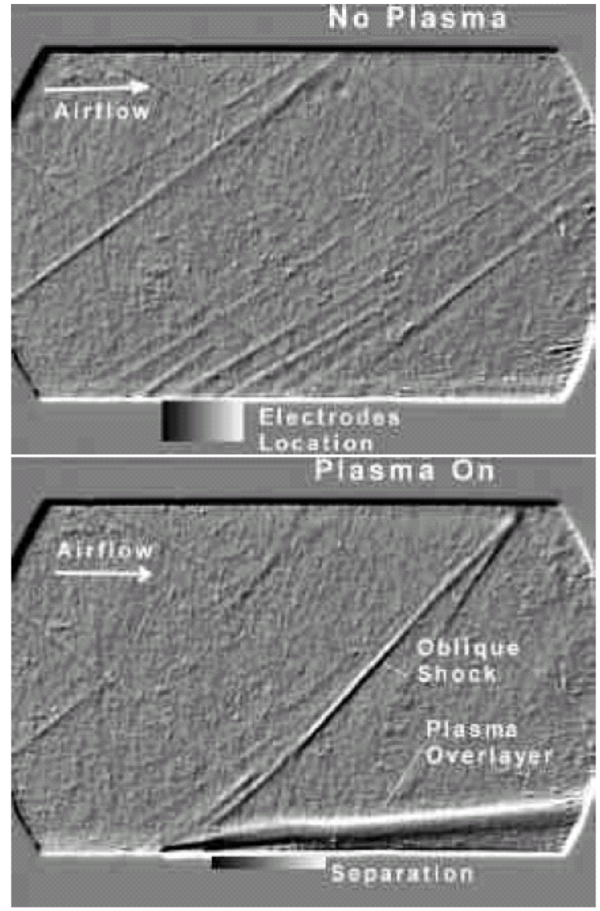
- Design and test multi-channel, high-voltage pulsed plasma generators, with individual channel power, frequency, phase, and duty cycle control
- Design localized arc filament plasma actuator / ceramic housing assembly
- Characterize and optimize actuator performance: measure arc filament discharge power and plasma temperature
- Determine effect of repetitively pulsed arc filament plasmas on high speed flow and acoustic noise

Previous results on high-speed flow modification: effect of solid obstacles and arc plasmas



Solid tabs in a circular M=1.3 jet flow: shear layer distortion by streamwise vortices

(Samimy et al., 2002)



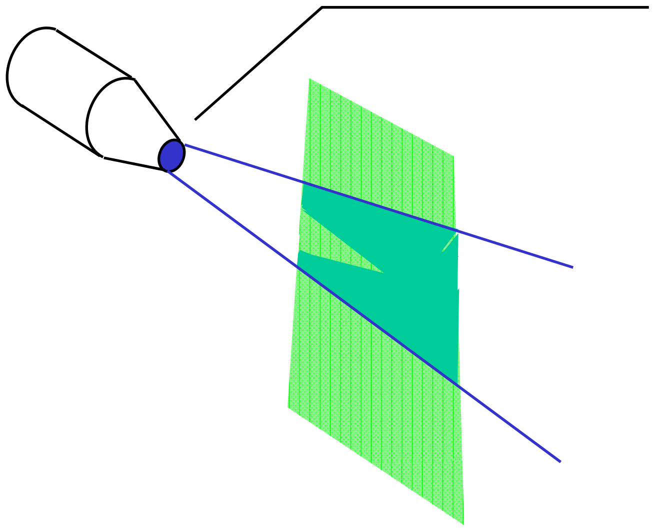
Near-wall DC arc plasma in flat plate M=1.5 flow: shock waves, flow separation

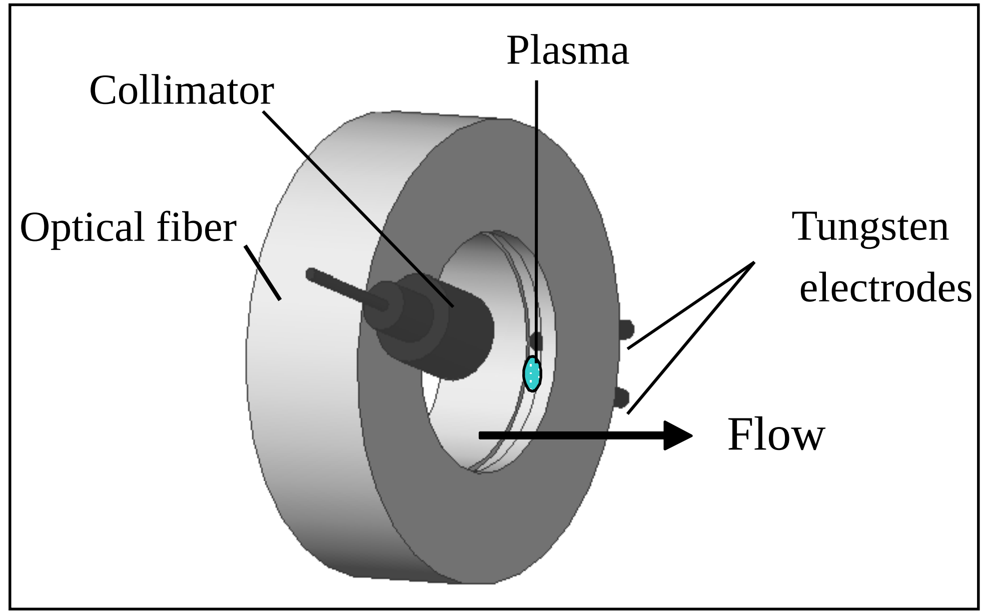
(Leonov et at., 2002)

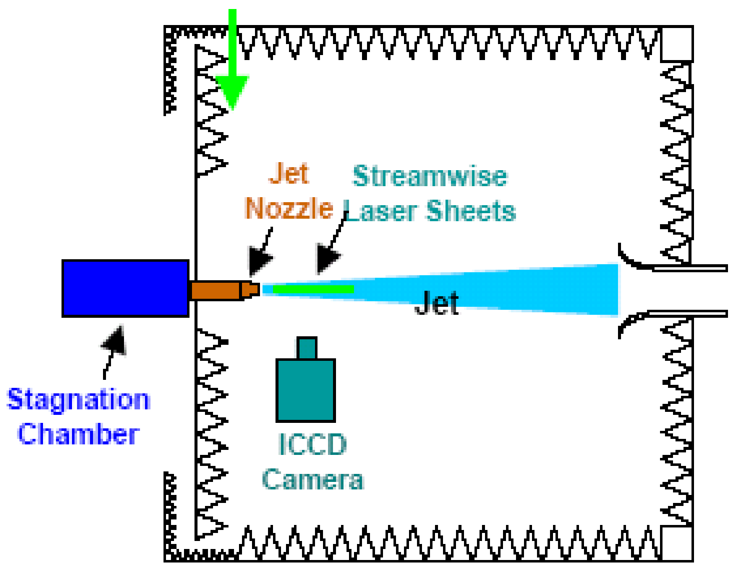
Key Technical Issues

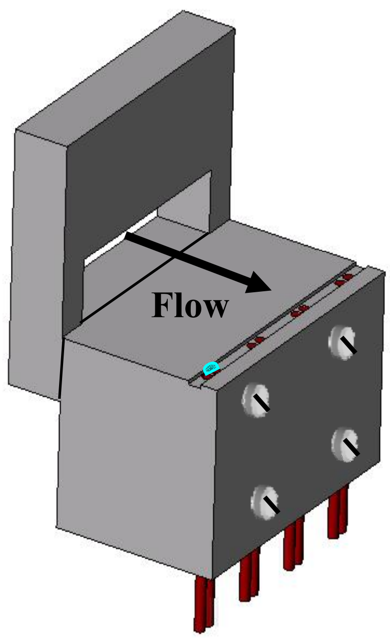
- **Solid obstacle actuators: always present in the flow, cannot operate in "on/off" regime at high frequencies**
- **Fluidic actuators: not enough bandwidth; piezo actuators: not enough amplitude**
- **Plasma actuators: combine high amplitude and bandwidth**
- **Sustaining and individual control of multiple arc filament plasmas: arcs are blown off by the high-speed flow**
- **Heating needs to be rapid and localized**
- **Plasma power needs to be small compared to flow power (~0.1%)**
- **Electrode and ceramic material erosion at high-temperatures**
- **EMI noise from the plasma**
- **Flow control mechanism and actuator optimization**

Experimental Facility Schematic

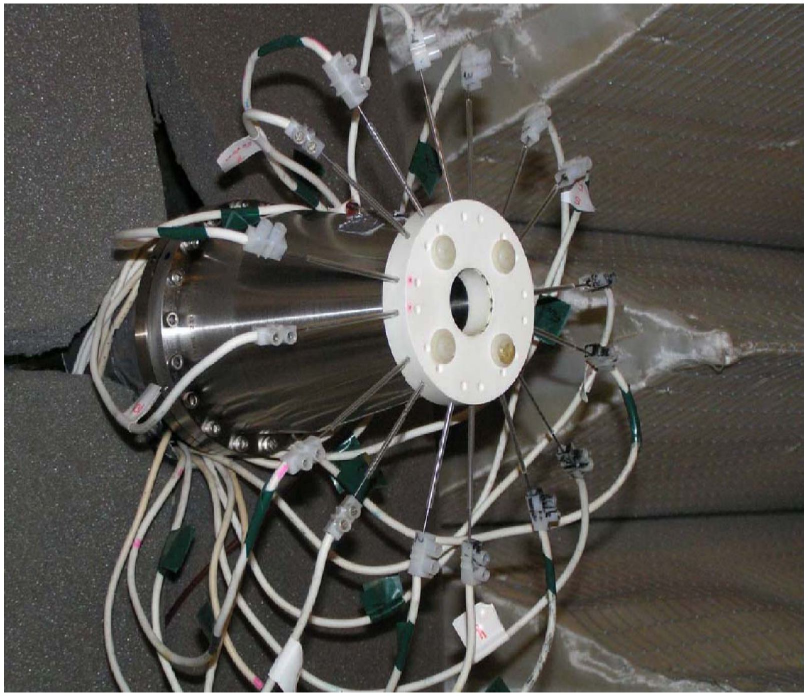








Circular and rectangular nozzle extensions

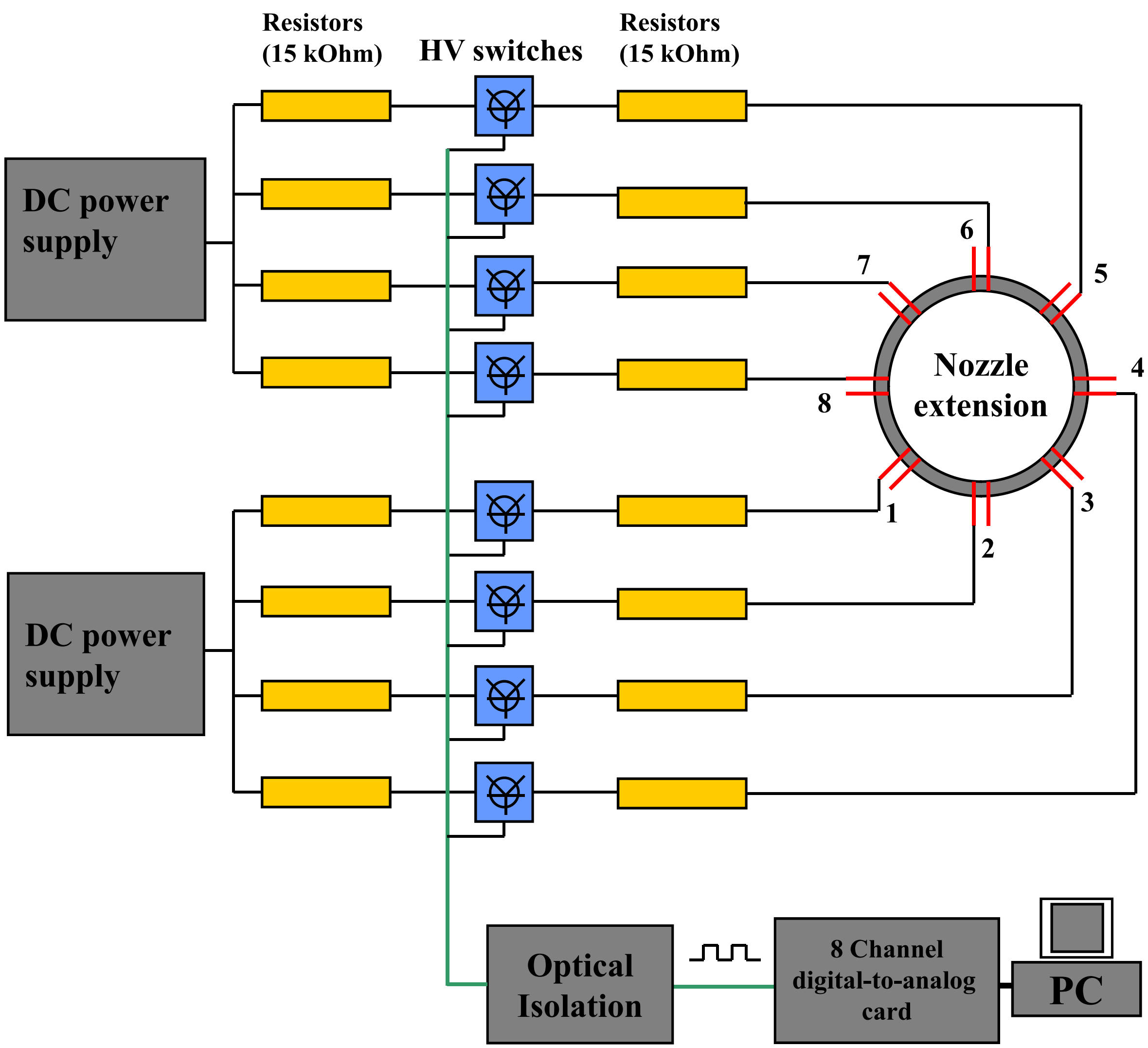


- Circular nozzle 1 inch in diameter
- M=1.3 correctly expanded jet
- 8 pairs of pin electrodes (3 mm apart)

- Rectangular nozzle, 1/2 in. x 3/2 in. cross section
- Flat plate nozzle extension
- M=0.9 jet
- 4 pairs of pin electrodes (3 mm apart)

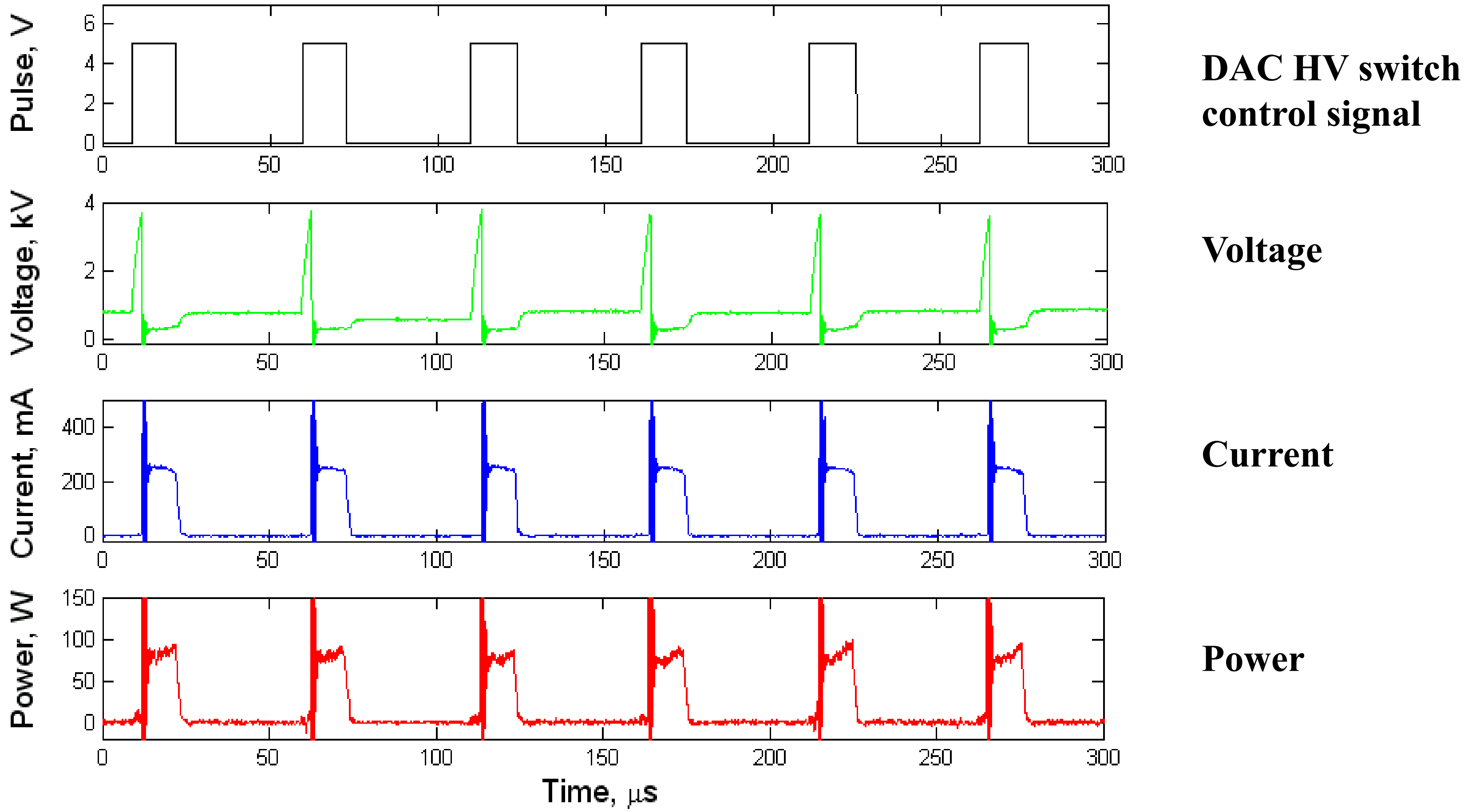
- Boron nitride nozzle extensions, tungsten wire electrodes
- Rectangular groove to stabilize plasma (1 mm x 0.5 mm)
- Visible emission: optical fiber / OMA spectrometer

8-channel high-voltage pulsed DC power supply



- Two 8 kV, 1.2 A DC power supplies
- 8 individually ballasted channels
- Fast HV switches in each channel (20 kV, 200 kHz, 0.1 μs response time)
- Switches controlled by independent waveforms generated by 8-channel DAC / Labview
- Optical isolator stops feedback EMI noise
- Independent control of frequency, phase, and duty cycle → excitation of different instability modes

Typical pulsed DC actuator waveforms

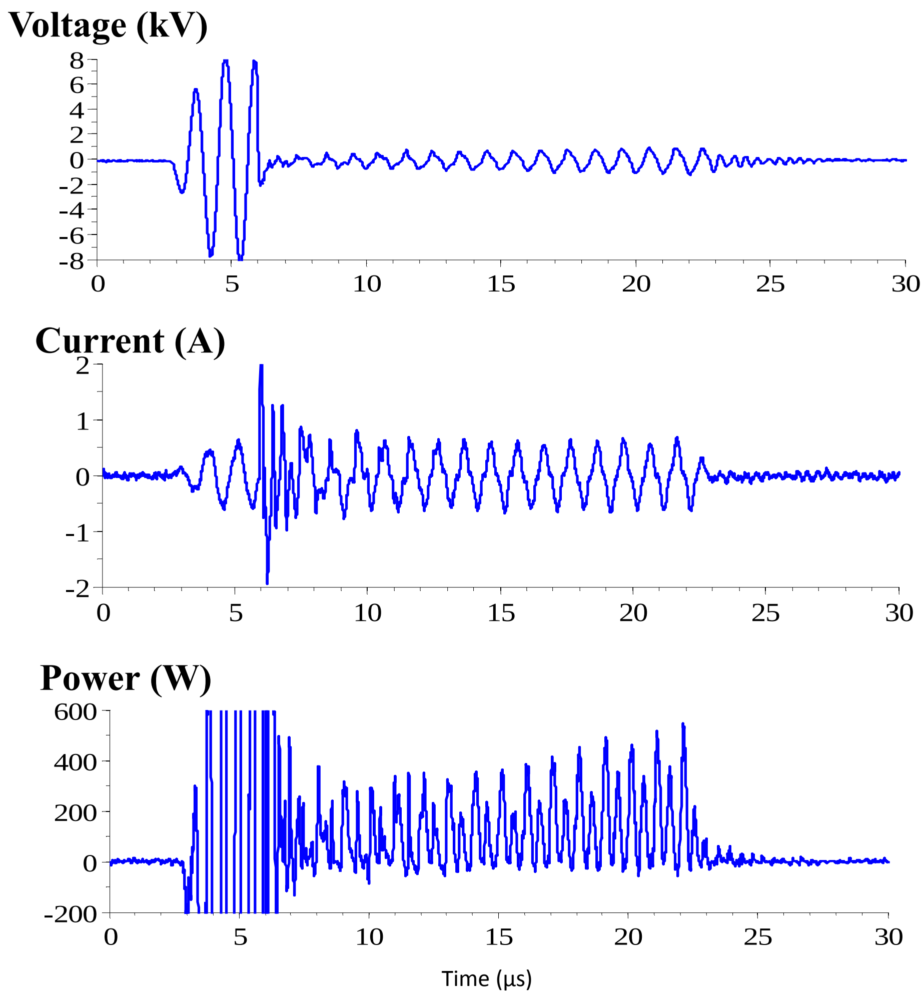


- M=1.3 jet power: 28 kW
- Time-averaged plasma power budget: ~20 W per actuator (160 W total) – 0.6%
- Down side: 90-95% of DC power supply power dissipated on ballast resistors

2-channel DC / pulsed RF converter power supply
(Heat and Mass Transfer Institute, Minsk, Belarus)

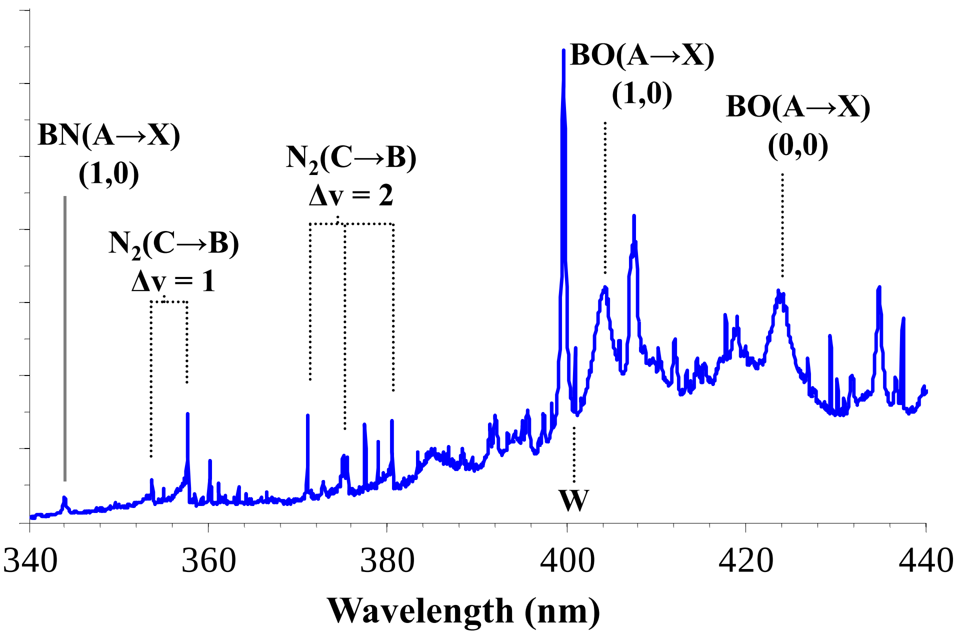
- **Input power: 400 V DC**
- **Output power: 20 kV peak, 1 MHz frequency RF pulse bursts, burst repetition rate 0-50 kHz**
- **Individual control of burst duration, repetition rate, and phase for individual channels → excitation of different instability modes**
- **Control signals generated by digital-to-analog card / Labview**
- **Rapid RF voltage ramp-up time: 1-2 μsec**
- **RF discharge after load breakdown: 500 V peak, 0.25 A peak, 100 W average power**
- **High DC / RF conversion efficiency: 60-85% of input DC power coupled to load**
- **No need for ballast resistors**
- **Scalable to large number of channels: 8-channel generator will be shipped in July, 64-channel is in design stage**

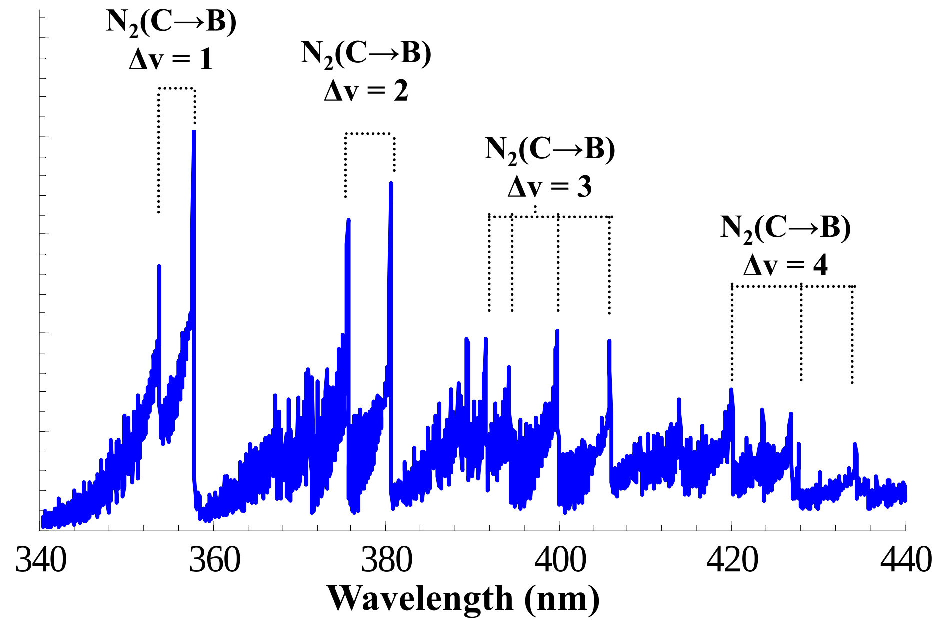
Typical pulsed RF actuator waveforms



- M=0.9 jet power: 37 kW
- Time-averaged plasma power budget: ~12 W per actuator (48 W total) – 0.13%
- DC/RF conversion efficiency: 60-85% of input DC power coupled to the plasma

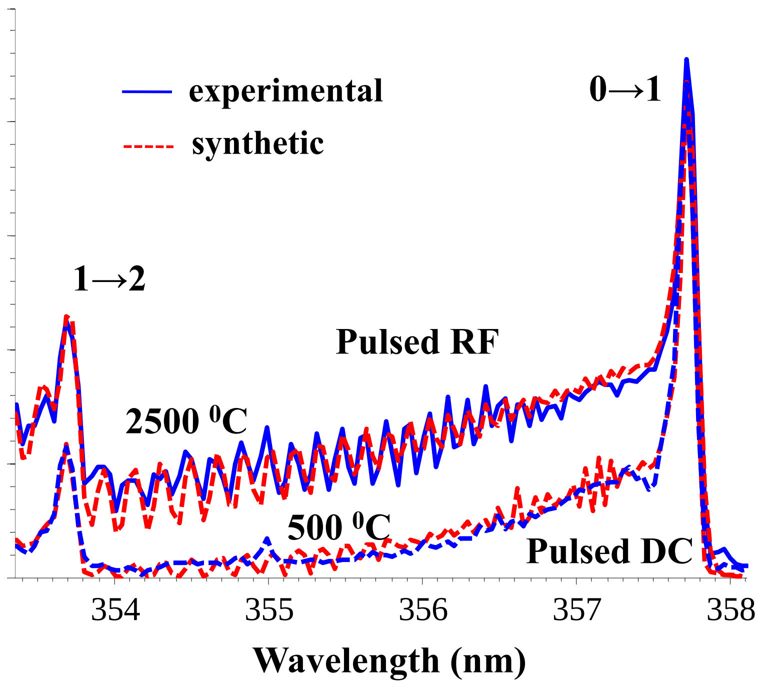
Pulsed DC and pulsed RF discharge emission spectra in a M=0.9 jet

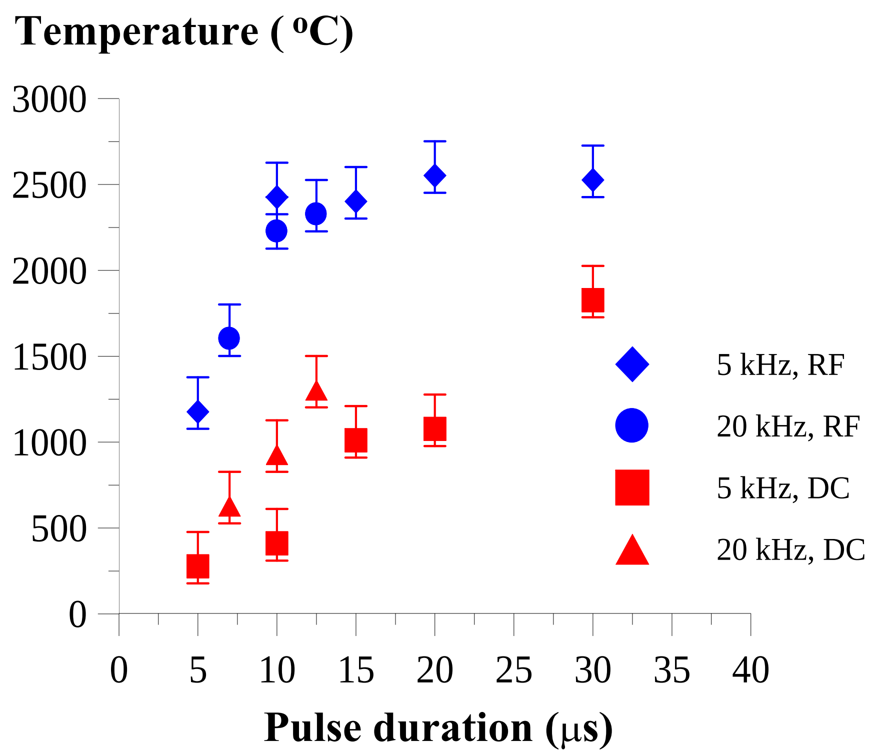




- **Signal collected only during "plasma on" periods (plasma rapidly blown off)**
- **Optical fiber signal collection region 2-3 mm in diameter**
- **Both spectra shown in the same scale**
- **DC discharge: broadband baseline (due to overlapping BO bands), BN and W atom emission (evidence of electrode and ceramic erosion)**
- **RF discharge: no boron oxide baseline (no apparent material erosion)**

Temperatures
in pulsed DC and pulsed RF discharges





- **Rapid heating rate in both discharges (~1000 ^{0}C over 10 μsec)**
- **RF discharge: much higher temperature (from $N_2(C^3\Pi_u \rightarrow B^3\Pi_g)$ bands) than in DC discharge at nearly the same discharge power**
- **RF discharge energy balance: more power to flow heating, less power to electrode / wall heating**

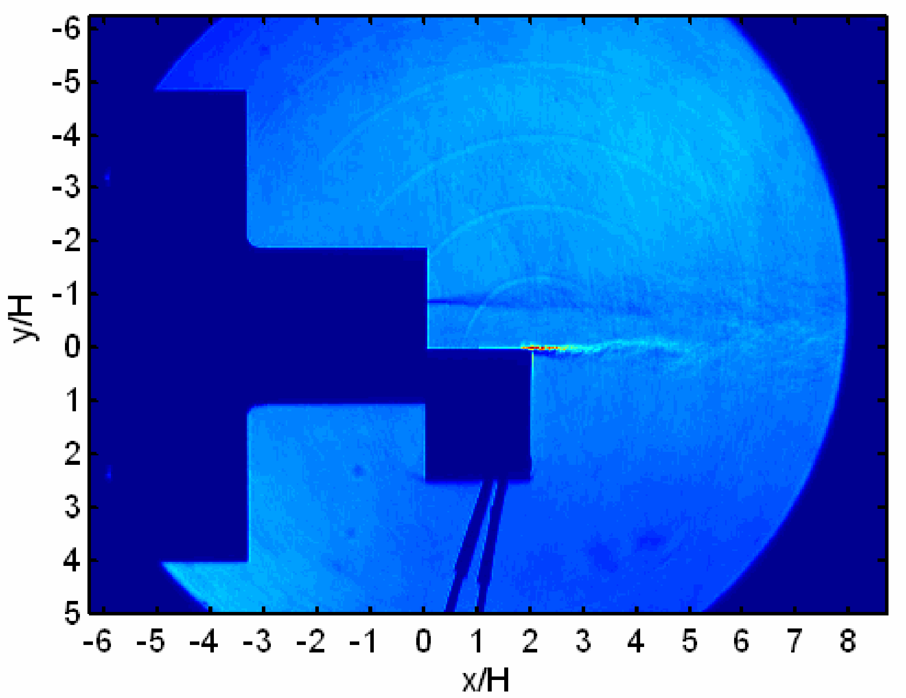
Compression / shock wave generation by rapid localized flow heating

Nonequilibrium Thermodynamics Laboratories

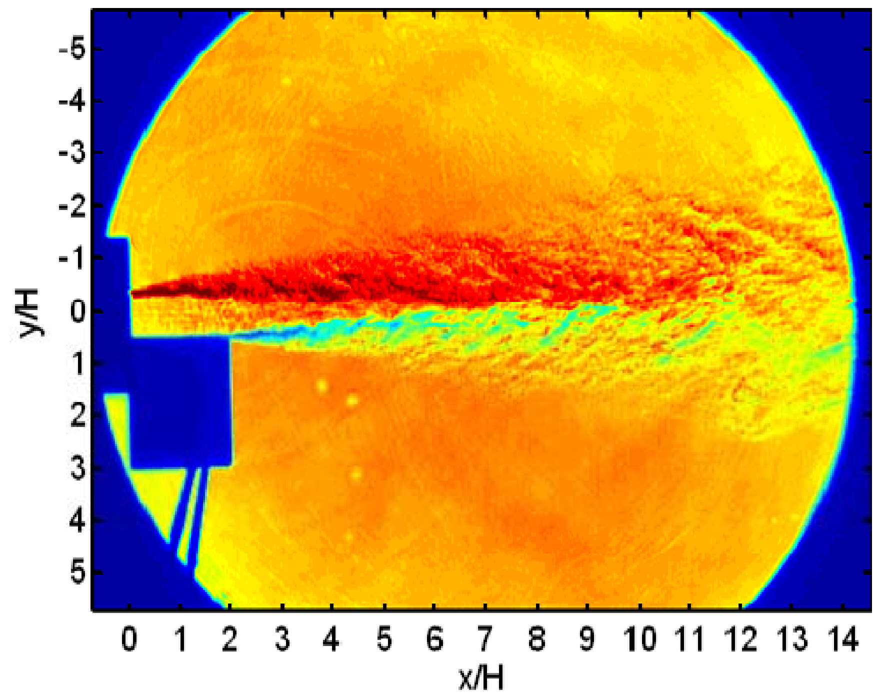
Gas Dynamics and Turbulence Laboratory

Pulsed DC, 20 kHz, 14% duty cycle

M=0.17



M=0.9

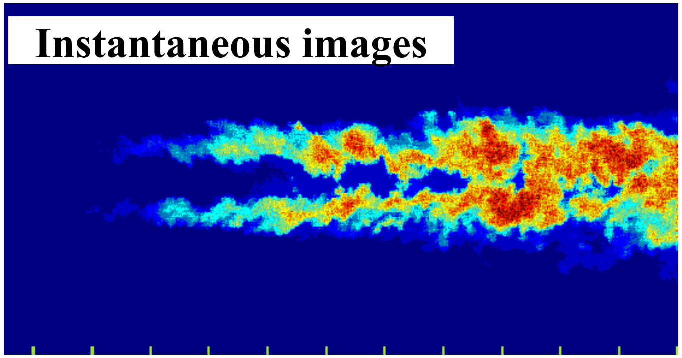


- Predicted by modeling calculations (Utkin et al., 2007)
- Rapid heating in arc filament → pressure rise → strong compression wave
- Amplification of repetitive pressure perturbations at "right" frequencies in jet flows (triggering jet column instability, shear layer instability)
- Flow interaction with pressure bumps may also result in streamwise vortices formation

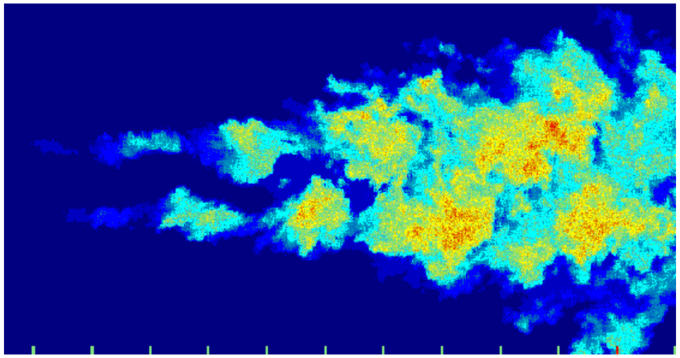
Laser sheet mixing layer visualization

Effect of different forcing frequencies

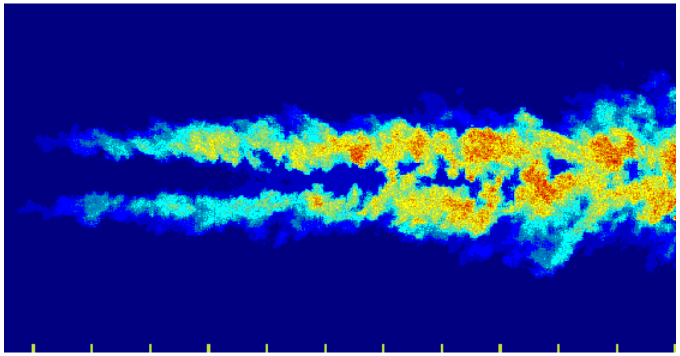
M=1.3 ideally expanded circular jet
8 pulsed DC actuators



Baseline (no plasma)

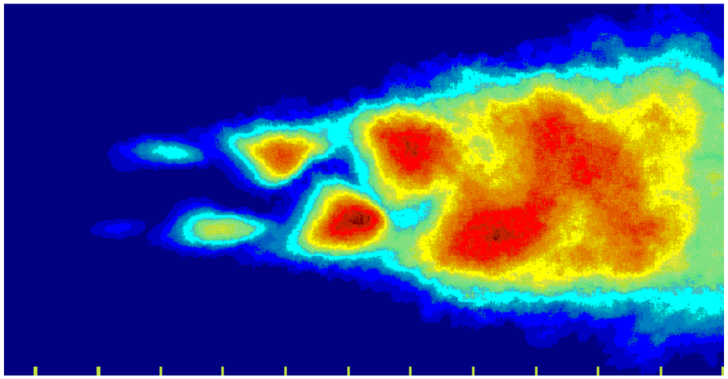


Flapping mode: 5 kHz (St_D=0.33) 5% duty cycle



Flapping mode: 20 kHz (St_D=1.3) 10% duty cycle

Phase averaged image

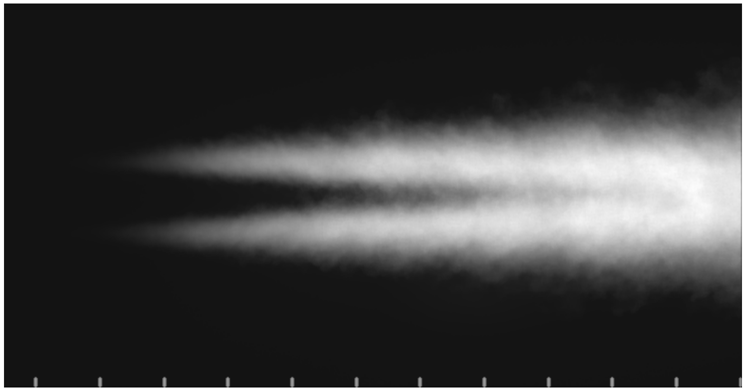


- **Flow strongly responds to forcing near jet column instability frequency**
- **Likely mechanism: growth of instabilities triggered by pulsed forcing**

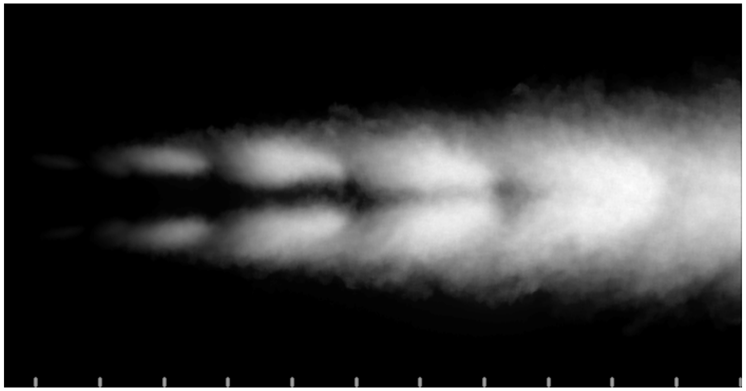
Laser sheet mixing layer visualization (cont.)

Phase averaged images, effect of different modes

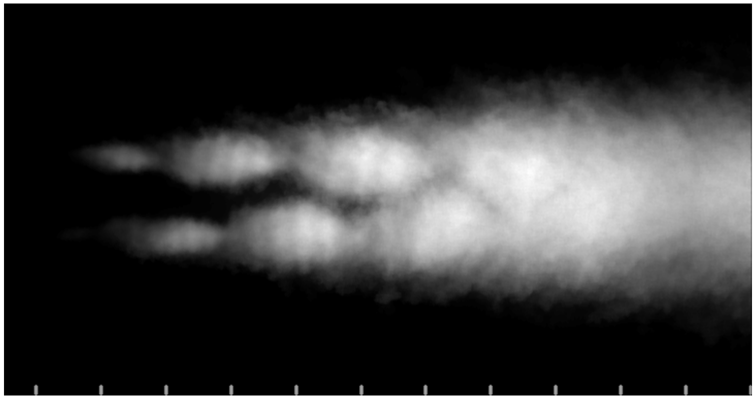
5 kHz, 5% duty cycle (10 μsec pulses, St_D=0.33)
M=1.3 ideally expanded circular jet, 8 pulsed DC actuators



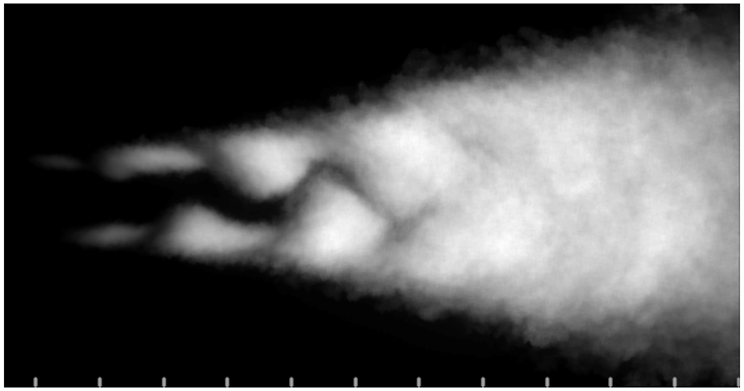
Baseline (no plasma)



Axisymmetric mode



First helical model



Flapping mode

Plasma Actuator / Flow Interaction Modeling

Actuators modeled as periodic temperature boundary conditions

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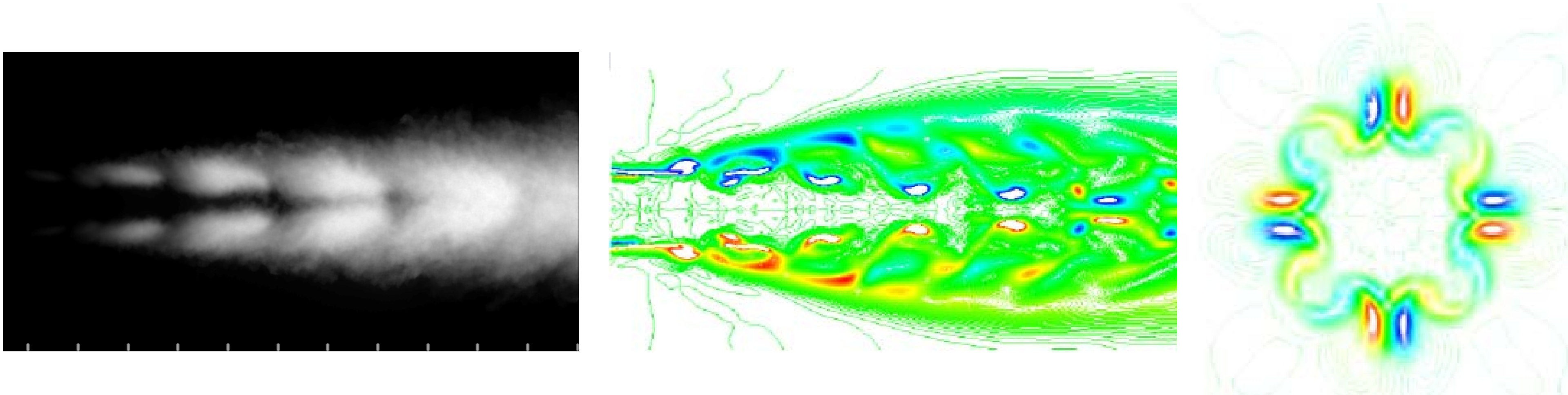
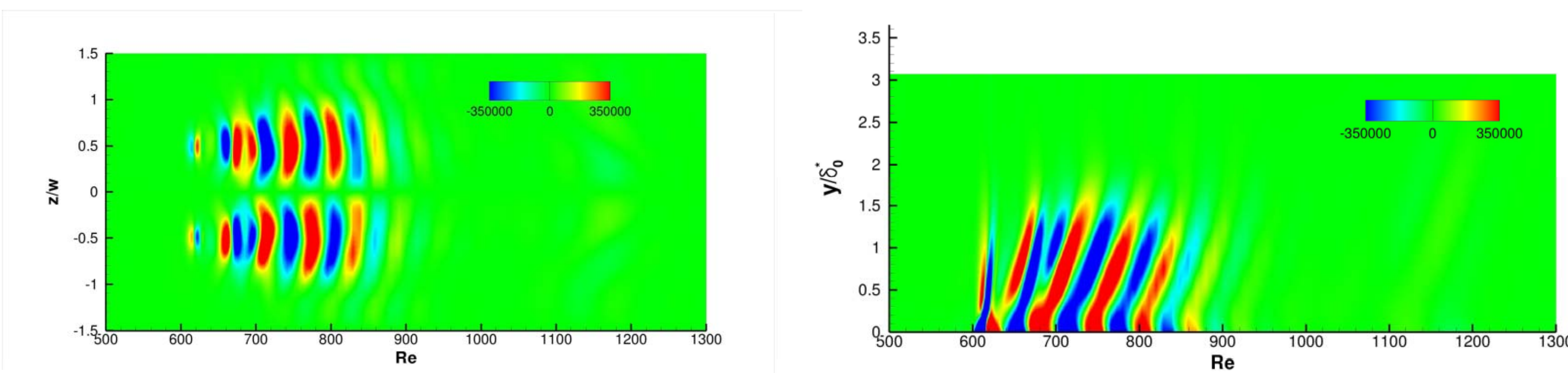


M=1.3 circular jet (3-D Euler equations, Yu et al., 2006)

Streamwise vortices predicted in calculations have not been detected in experiments

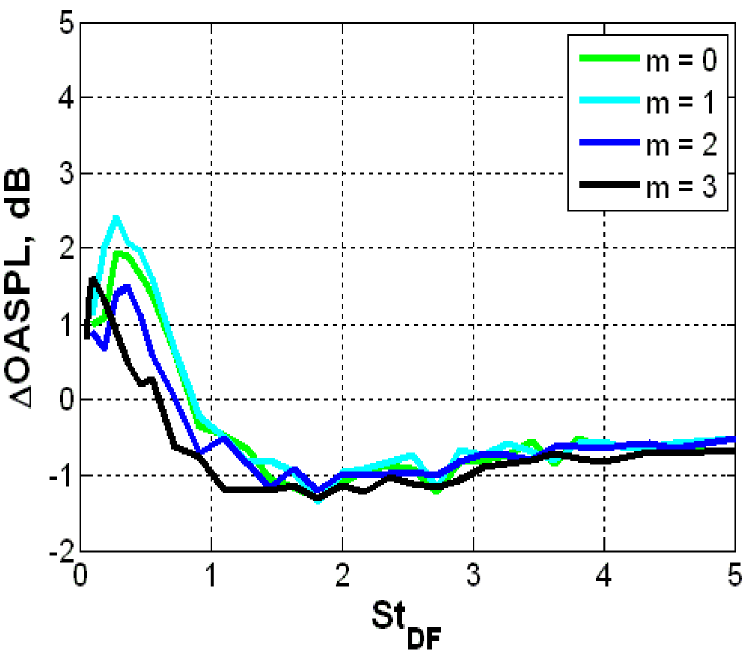


M=1.5 flow over flat plate (3-D Navier-Stokes equations, Yan and Gaitonde, 2008)

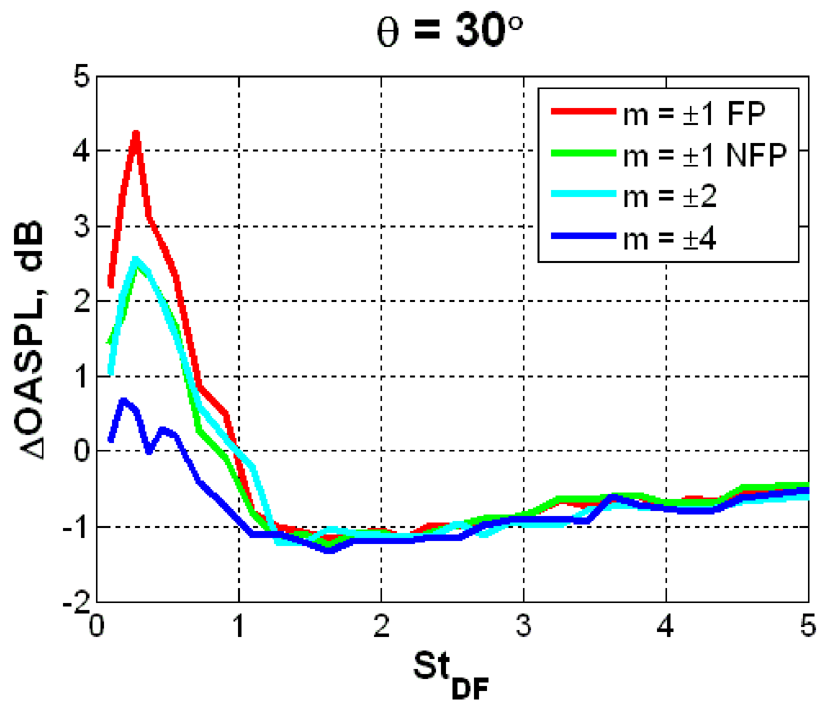
Streamwise vortices formation due to flow interaction with pulsed pressure bump

Plasma Effect on Acoustics: Far-field Sound Pressure Level Reduction

M=0.9 circular jet



Axisymmetric and helical modes



Flapping modes

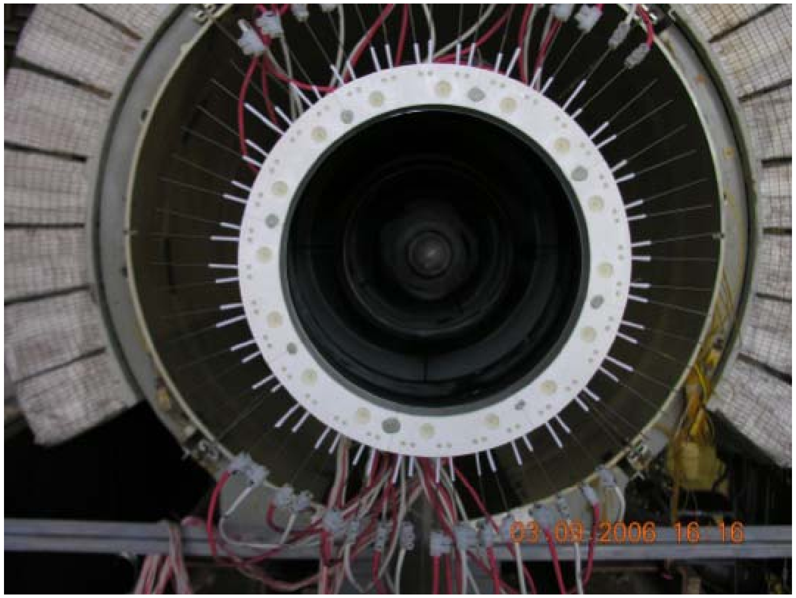
Noise reduction (by 1-2 dB) achieved at higher forcing frequencies than mixing enhancement (St_D=1-3 vs. St_D=0.33, Samimy et al., 2006)

Summary: High-Speed Plasma Flow Control

- **Multi-channel, high-voltage, energy efficient pulsed power generators, with individual channel parameter control designed and tested**
- **Arc plasma actuator / BN ceramic housing assemble designed and tested**
- **Discharge parameters and arc filament plasma temperature measured**
- **Plasma power does not exceed ~0.5% of jet power**
- **Filament heating: up to ~2500^0 C over ~20 μsec**
- **Compression / shock wave formation by pulsed arc filaments detected**
- **Effect of pulsed plasma actuators on mixing rate and noise reduction demonstrated**
- **Likely flow control mechanism in jets and shear layers: growth of flow instabilities triggered by repetitively pulsed forcing**

Future work

- **Development of a massively multi-channel (64 channels), energy efficient, pulsed RF plasma generator and actuator array to force large diameter jets (funding permitting). Currently, 8 out of 32 available actuators used in 7.5 inch diameter jet.**
- **This approach may well become practical for mixing enhancement and noise reduction in jet engines**



7.5" jet nozzle
at NASA Glenn NATR facility

32 actuators are shown

Acknowledgments

- **U.S. Air Force Office of Scientific Research (Julian Tishkoff, technical monitor)**
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Thank you for your attention!