Project 70

Reduction of nvPM Emissions from Aero-Engine Fuel Injectors

Georgia Institute of Technology & Honeywell. Inc

PI: Wenting Sun

Co-PI: Adam Steinberg (GT), Ellen Mazumdar (GT), Rudy Dudebout (Honeywell)

PM: Prem Lobo

Cost Share Partner(s): Honeywell International, Inc.

Objective:

- Characterize the formation and oxidation of non-volatile particulate matter (nvPM)
- Understand the effect of Jet A and SAF

Project Benefits:

- Improve the understanding of nvPM formation/oxidation and develop numerical models to guide new fuel injector design.
- Provide experimental validation data to Proj. 71
- Complementary to engine tests
- Enable cleaner aircraft engines compliant with the ICAO CAEP/11 nvPM LTO standard

Research Approach:

- Experiments on high pressure combustor with three liquid fuel injectors
- Variety of optical diagnostics (OH PLIF, LII) and sampling at practical engine conditions
- Numerical simulations to understand underlying nvPM formation mechanisms

Major Accomplishments (to date):

- A unique high pressure combustor with three fuel injectors commissioned
- Comprehensive numerical simulations were conducted

Future Work / Schedule:

- Systematic experimental measurements on Jet A, SAF and their blends
- Comparison between modeling and experiments
- Extractive sampling measurement on nascent soot, NOx, and CO

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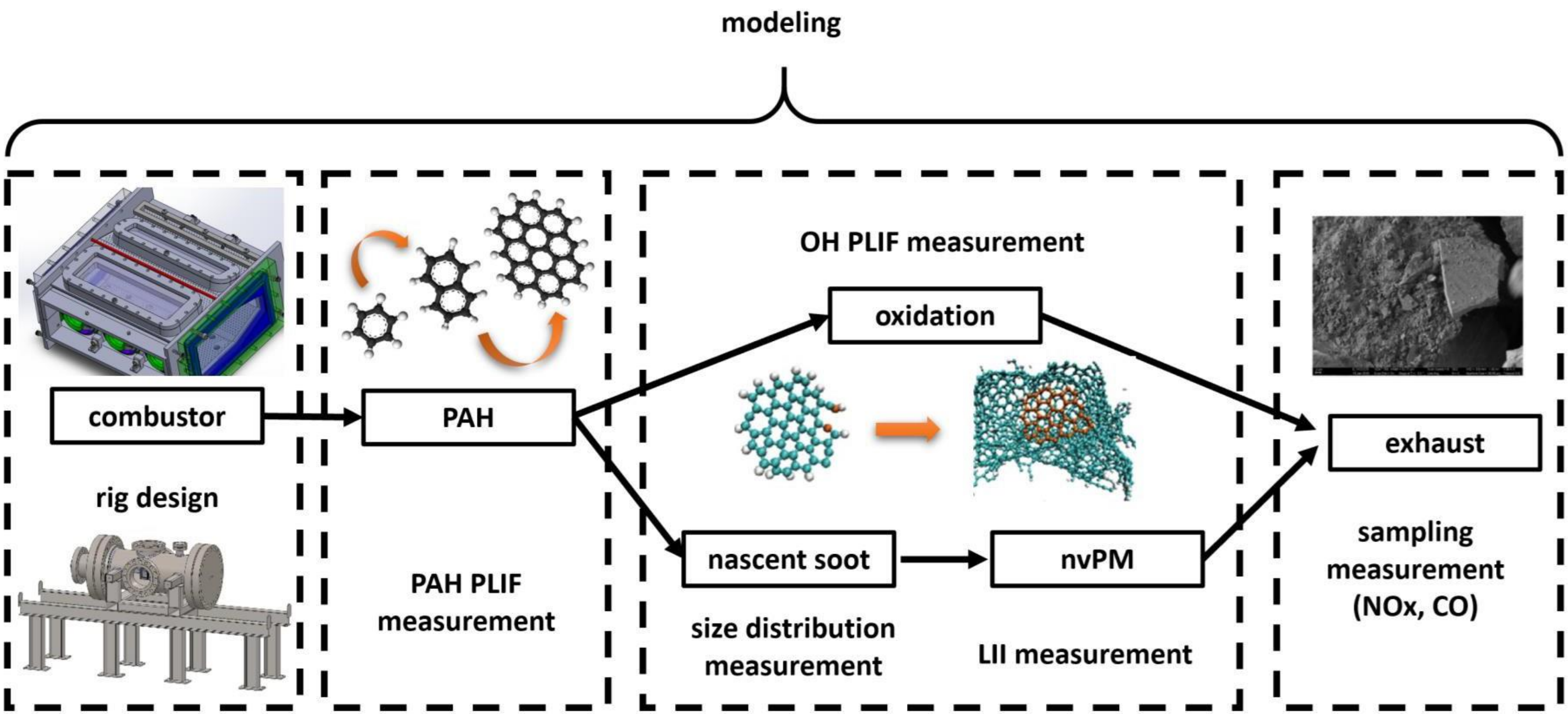
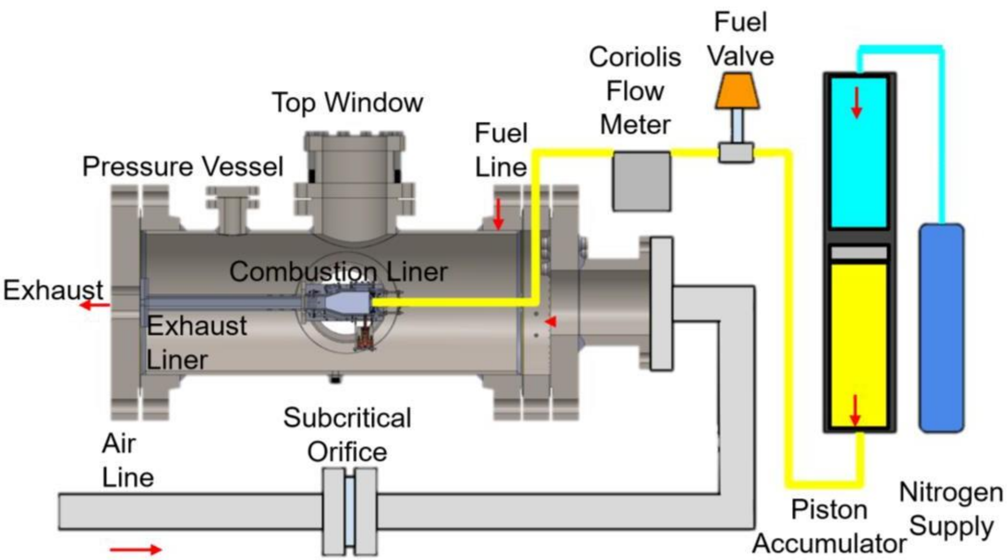
Project Overview

- Tasks include new rig design and systematic characterization of nvPM
- Comprehensive numerical simulations to compare with experiments
- Experiments on both conventional jet fuel, SAF and their blends



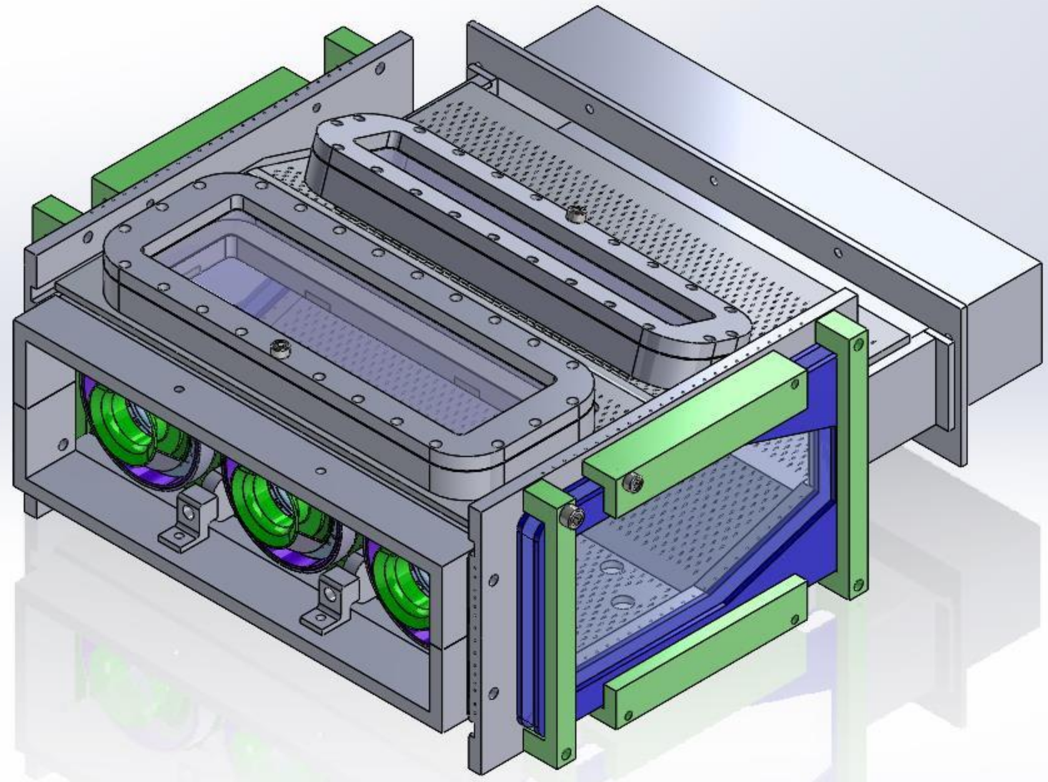
Development of High Pressure System

- Started from scratch in 2020…



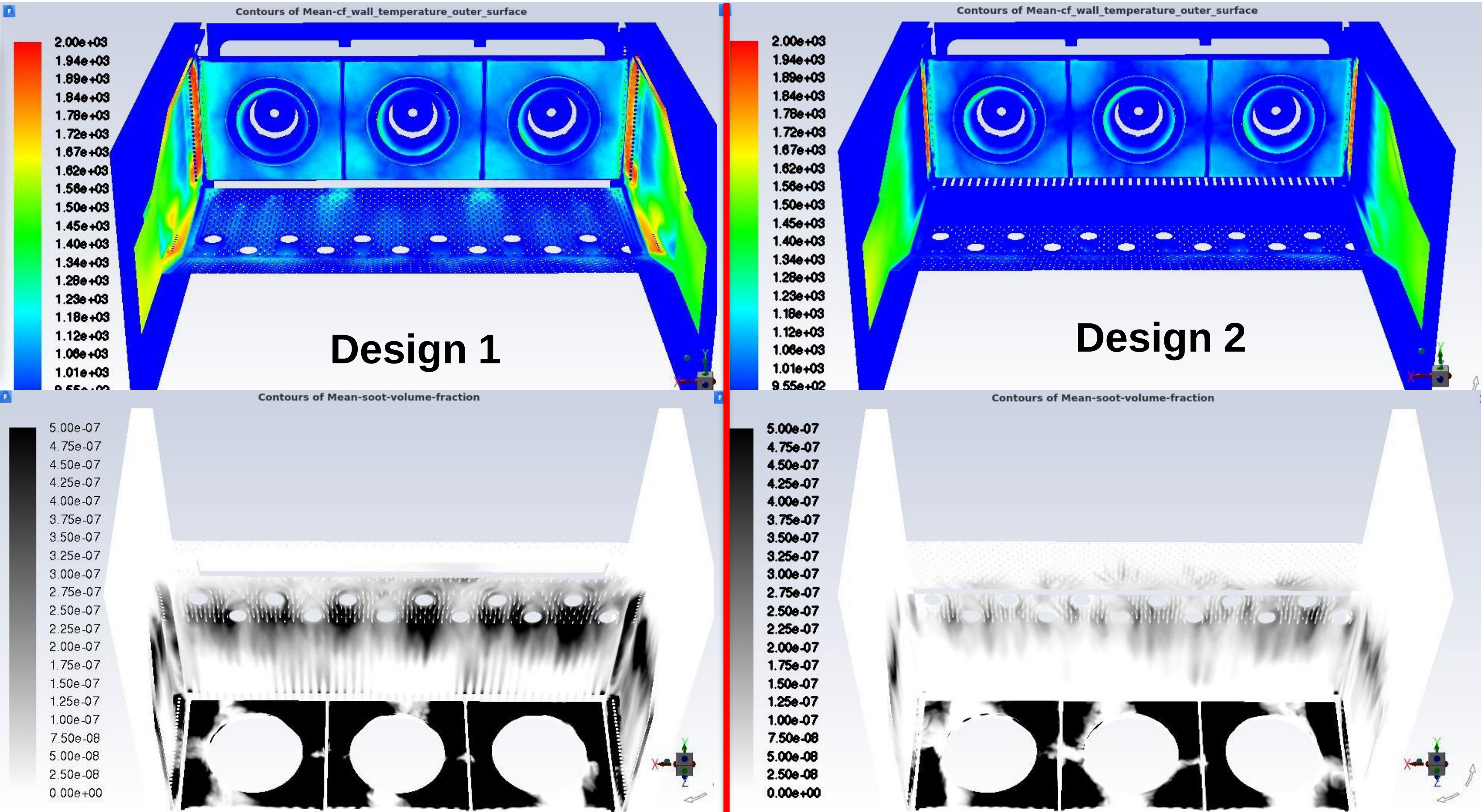
Combustor Design with CFD Assistance

- Identify hot spot
- Design cooling pattern
  - Dome edge cooling
  - Liner secondary zone cooling
  - Windows cooling
- Soot prevention on windows
- LES simulation



Combustor Design with CFD Assistance

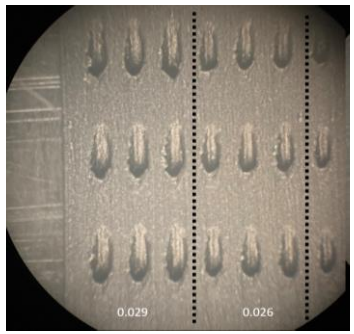
- CFD assists combustor design
- Wall temperature (K) & Soot volume fraction

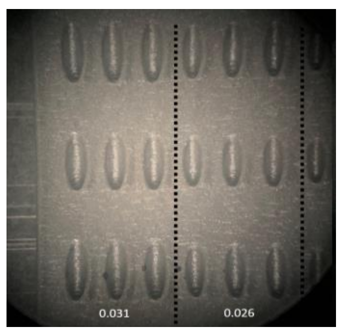


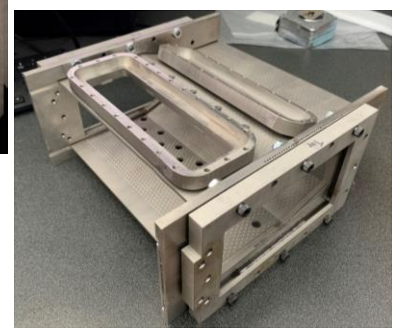
Combustor Design and Fabrication

- Additive manufacture

2 A.M. in lab

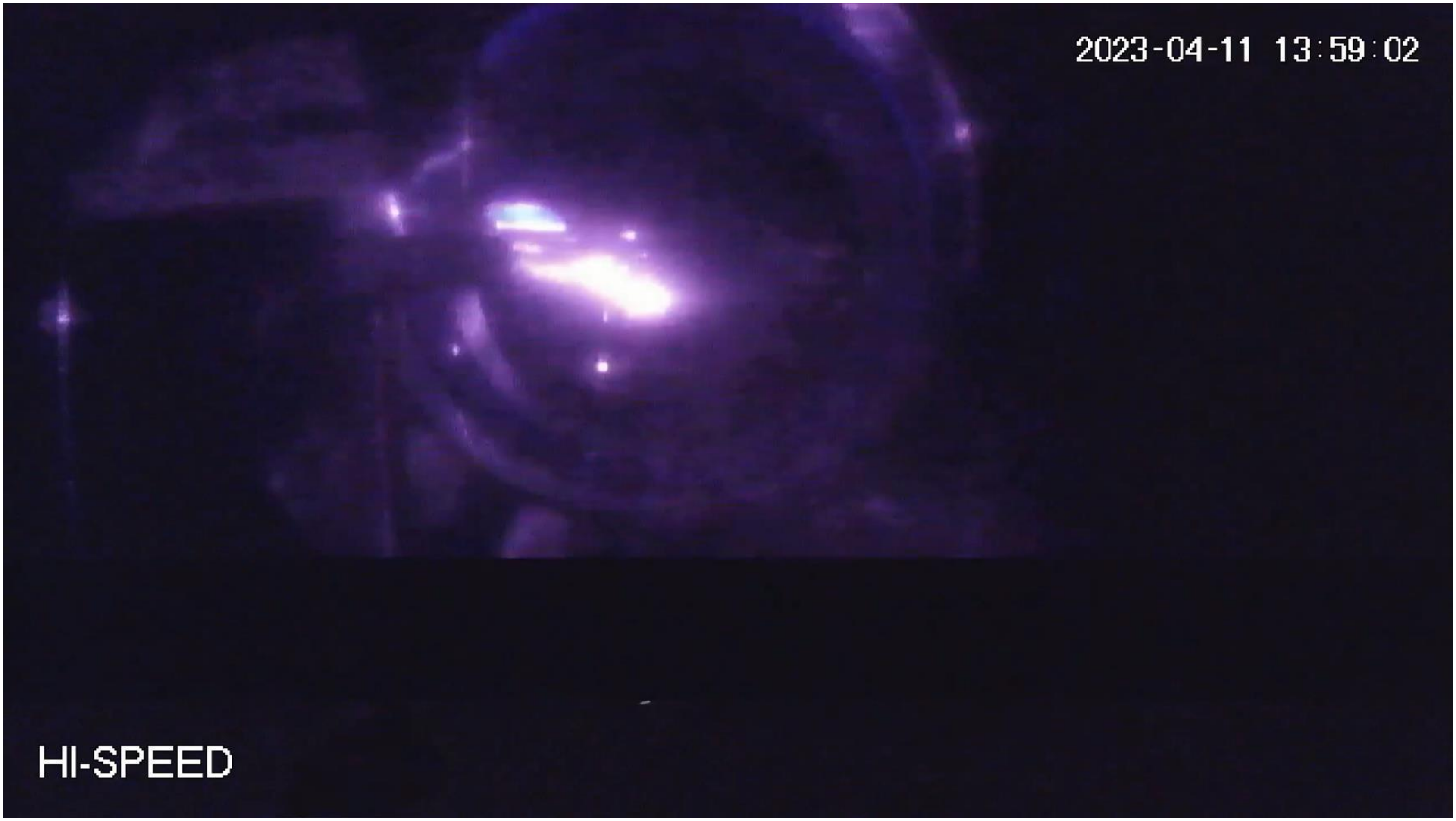






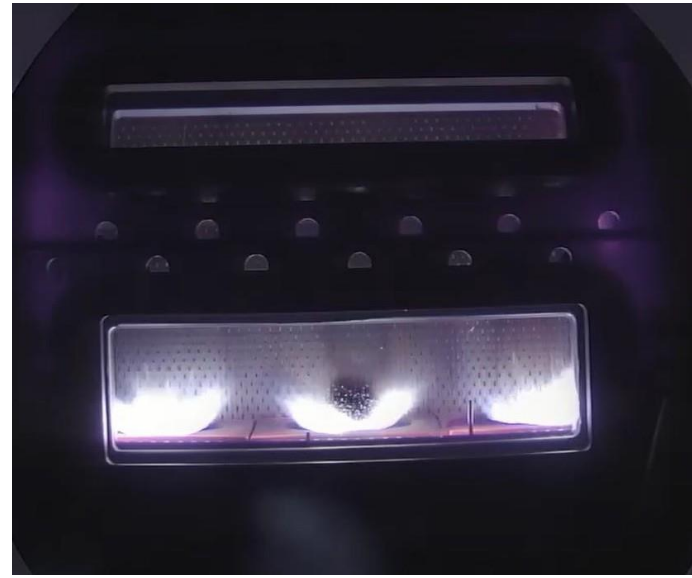
Combustor Operation

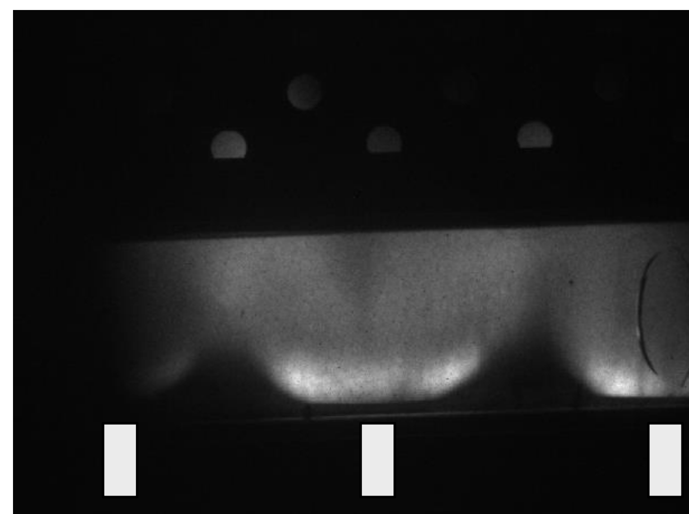
- 4.35 atm, 500 F air, jet-A, sideview



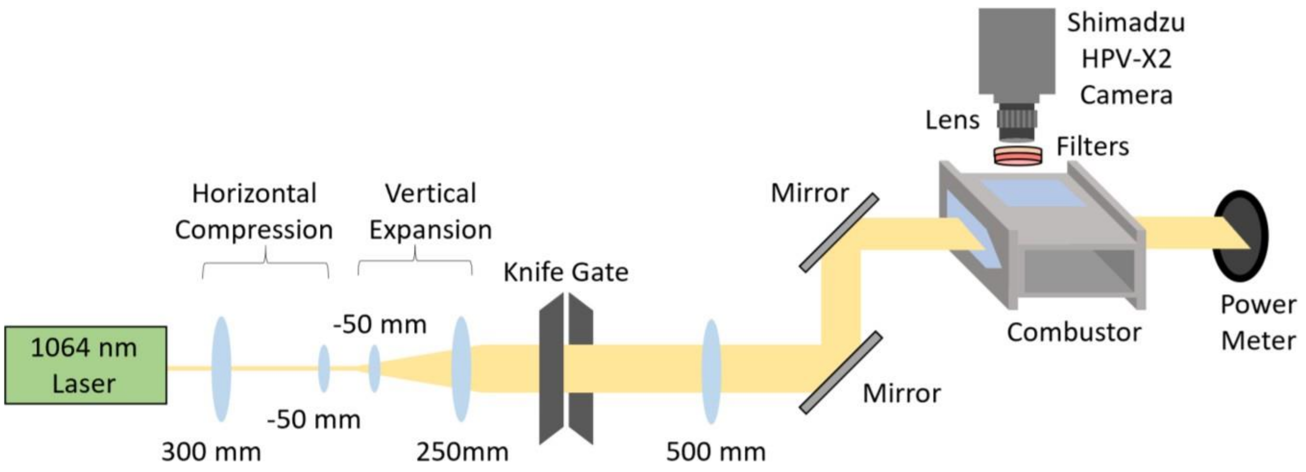
Combustor Operation

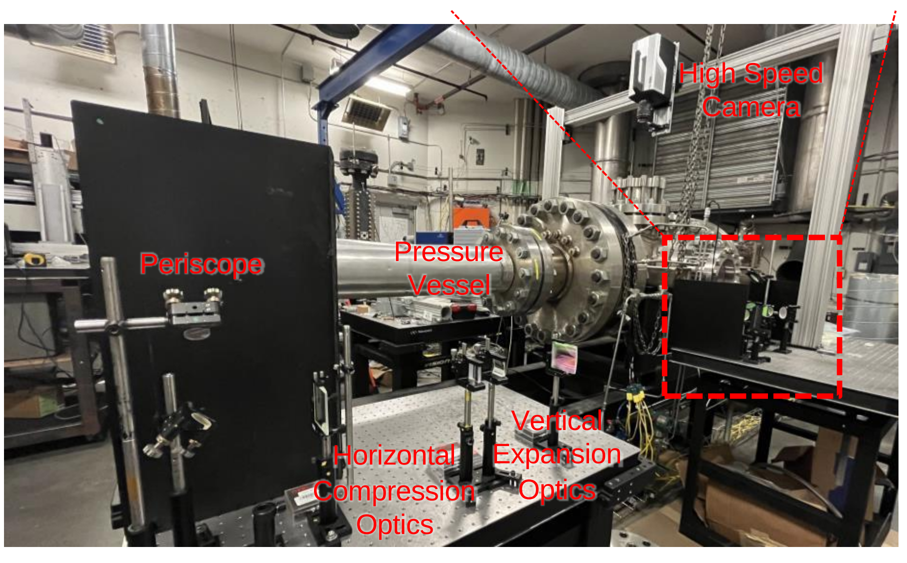
- 10 atm, 450 F air, jet-A, topview





Laser Diagnostics for Soot Volume Fraction



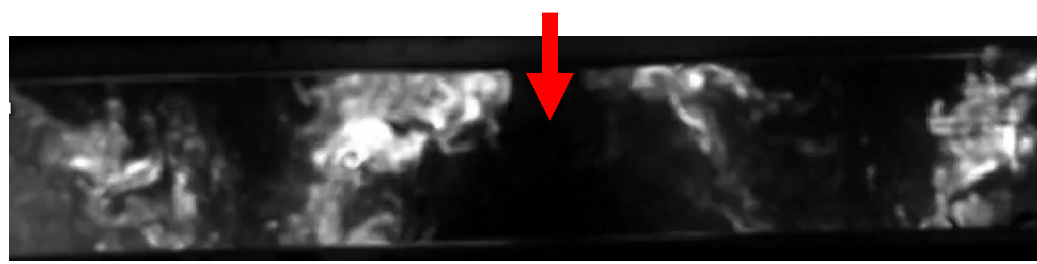


- Quanta-Ray Pro 250, 1064nm with max 2 J/pulse
- Top hat sheet dimensions: ~2mm x 35.5mm
- Typical average fluence: 0.05 - 0.17 J/cm^2
- Filters used: 1064 bandstop and 640 nm (75 nm FWHM) bandpass
- Ultra High-speed Shimadzu HPV-X2 (10 MHz zig-zag interpolation, 55 ns exposure, 32 micron pixel size)
- Power meter used to determine laser absorption for soot volume fraction estimation

TiRe-LII Measurement

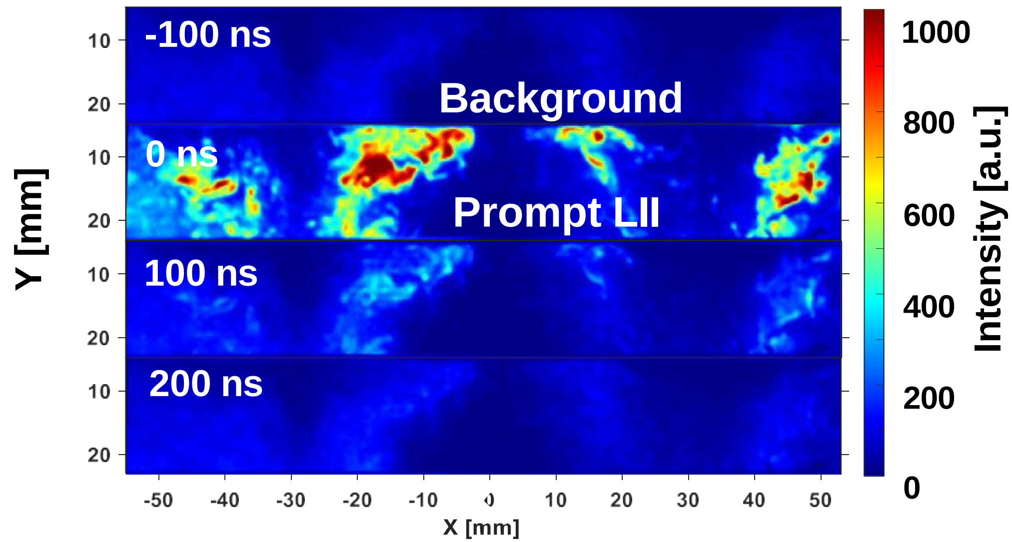
- Top view of injectors
- Data acquired at 500 ° F, 64 psi, laser fluence of 0.12 J/cm^2
- Beam width 35 mm
- 5 mm distance from injector dome face
- Due to large field of view, pixel resolution are 250 – 500 microns per pixel
- Prompt LII frame is bright, no intensification needed
- Second frame also bright, can fit time constant to image
- Turbulent flame features are visible from spray cone of each injector

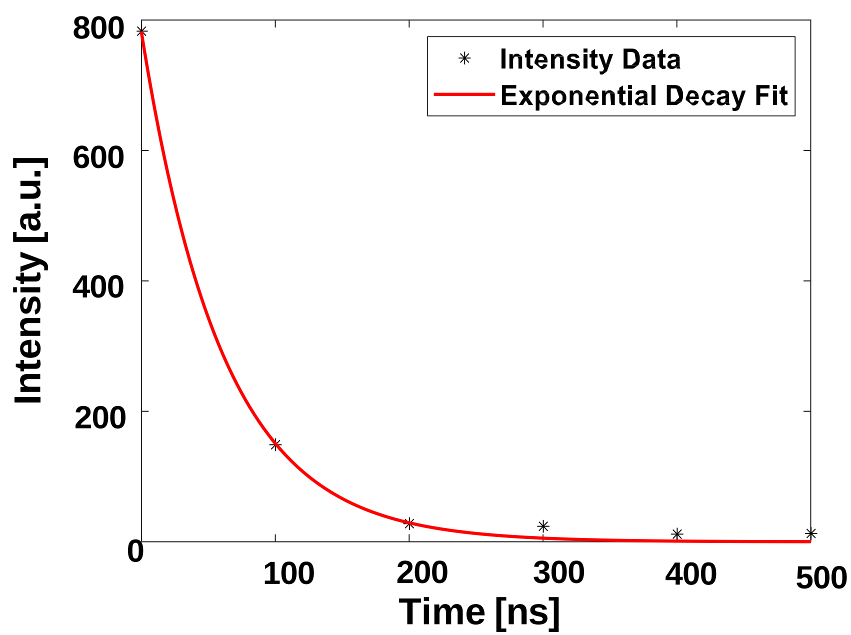
Center of middle injector



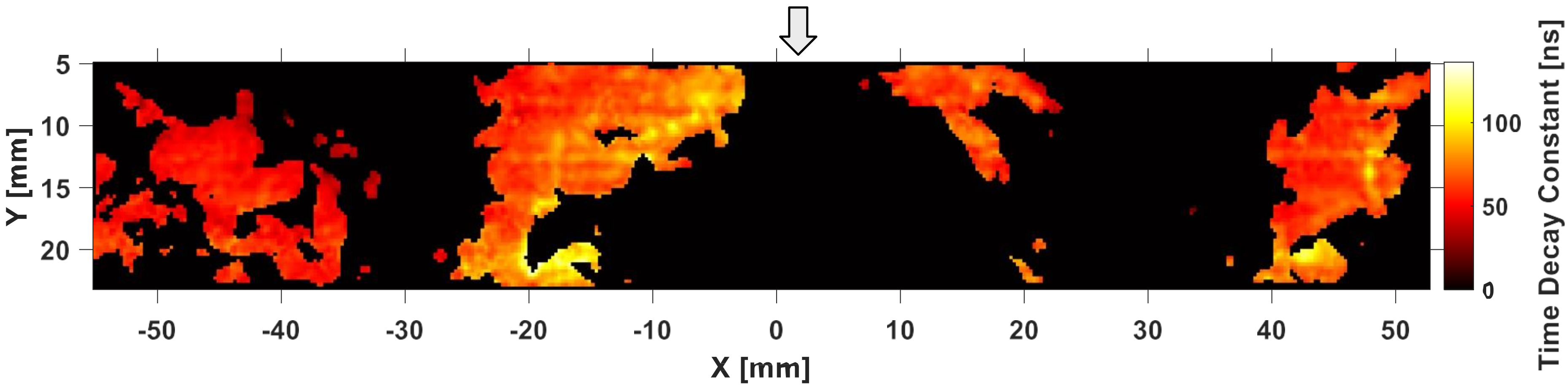
TiRe-LII Measurement

- Prompt LII signal provides qualitative volume-fraction soot measurement
- Thermal decay per pixel is approximately exponential
- Time-resolved data can be used to calculate time constant of decay
- Can be combined with LII heat transfer models to determine soot particle size assuming an agglomerate size or vice versa



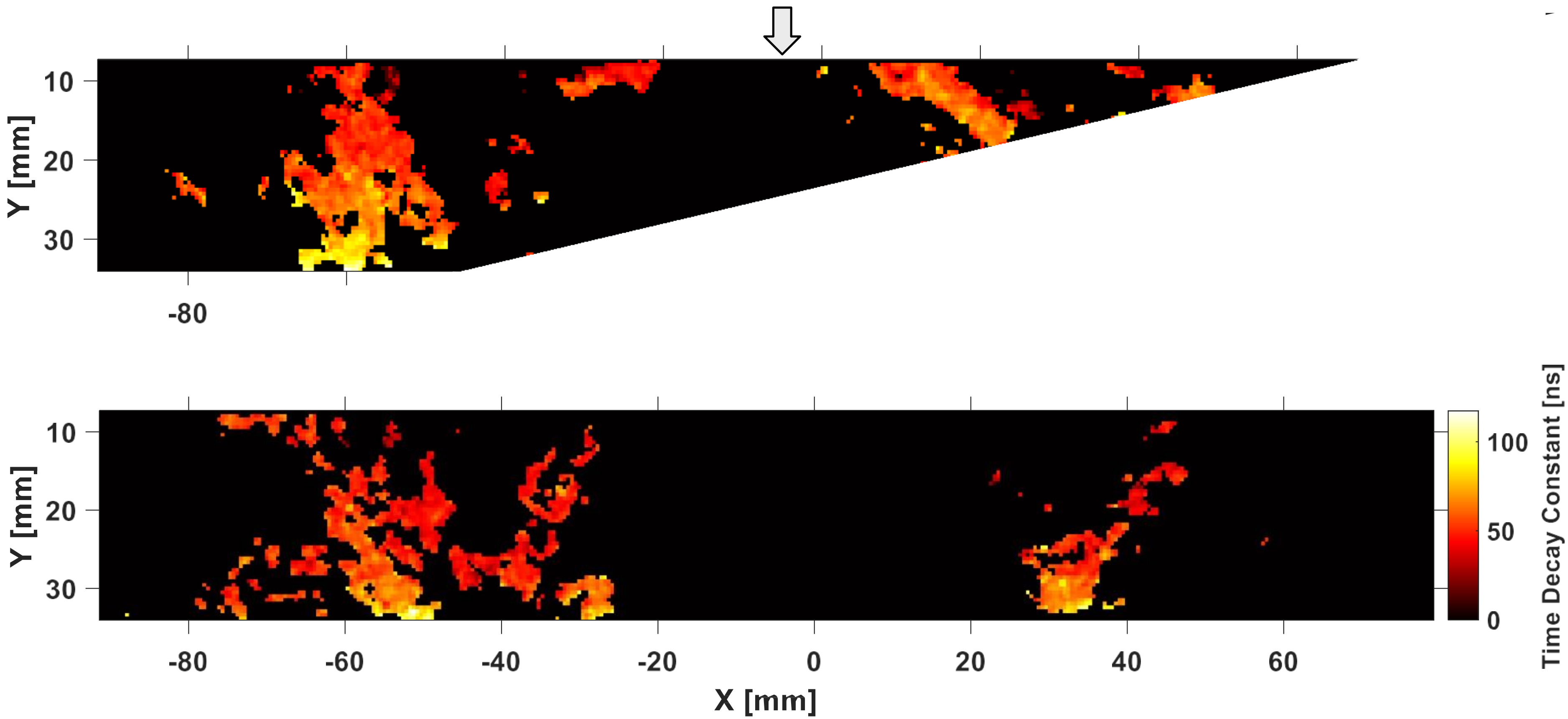


Time Constant from LII



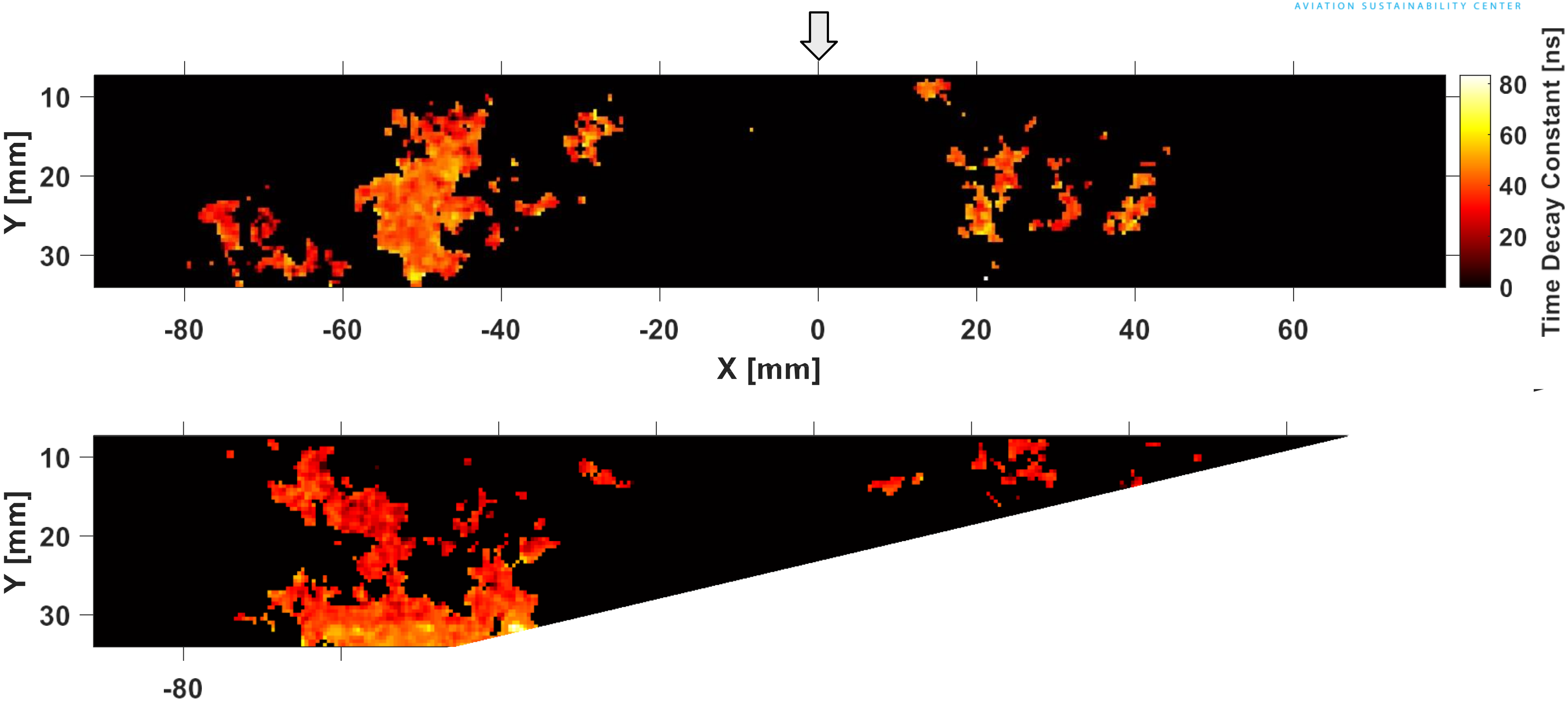
- 2D spatially resolved image of soot distribution
- Time constants can be fit to an LII model to estimate particle size, additional diagnostics (for unknown parameters) in progress
- Time constant data still shows qualitative trends in terms of how particle size changes with pressure, location, fuel/air ratio, and temperature

Results at 37.5 psi



- Higher time constants downstream appear to suggest downstream soot particle agglomeration

Results at 82.8 psi

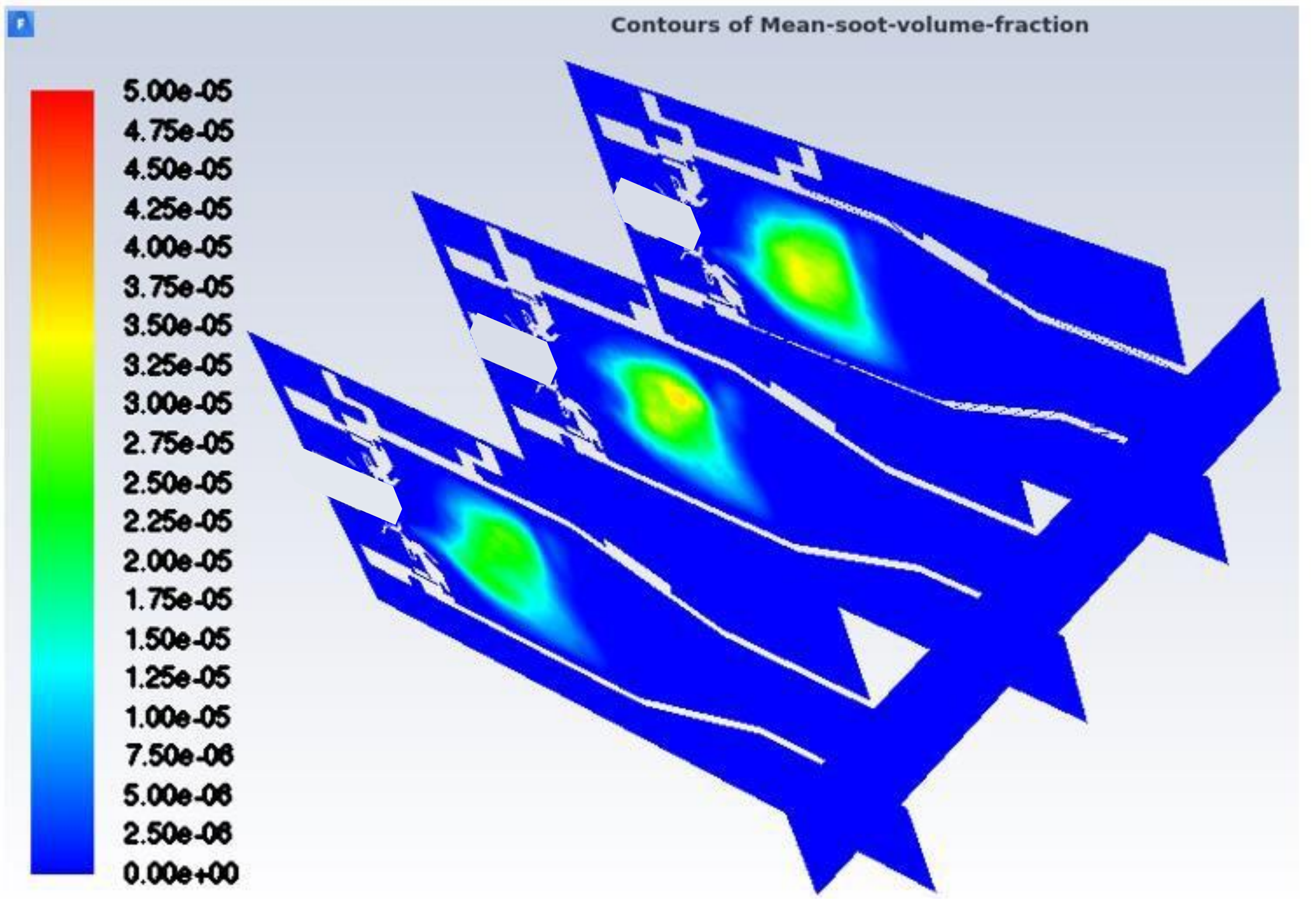


- Does not have the same downstream increase in time constant as 37.5 psi condition
- Ongoing tests at different pressure conditions

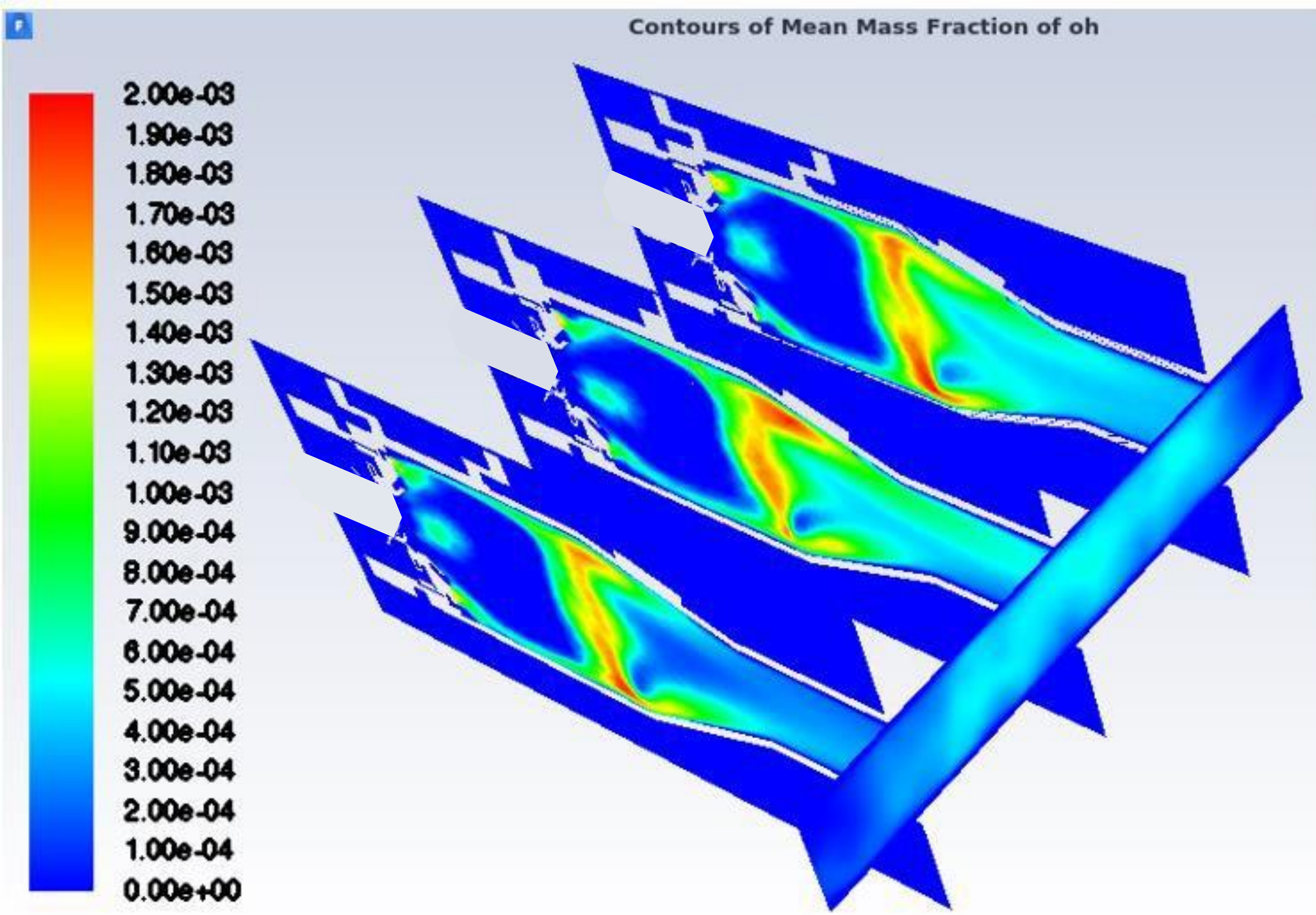
Numerical Simulation

- LES simulation
  - Soot/NOx distribution

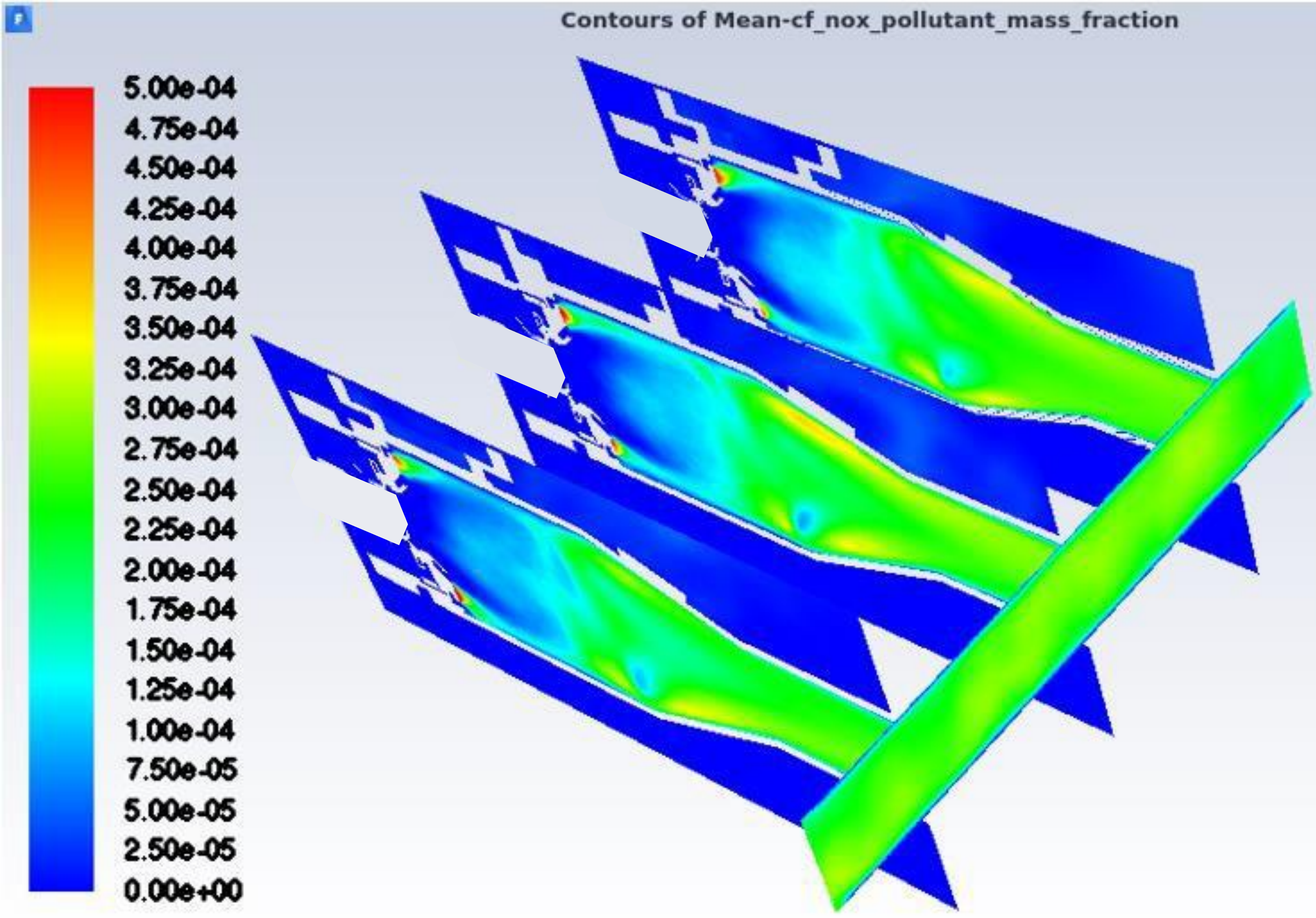
Mean Soot Volume Fraction



Mean OH Mass Fraction



NO Mass Fraction



Summary

- High pressure combustor with three fuel injector commissioned
- Investigated nvPM formation in combustor through combined experimental and numerical approaches
- More diagnostics currently in progress
  - OH PLIF, extractive sampling for nvPM size, NOx, CO
- Synergy with Project 71
- Complimentary to Honeywell's engine testing results

Thank you!

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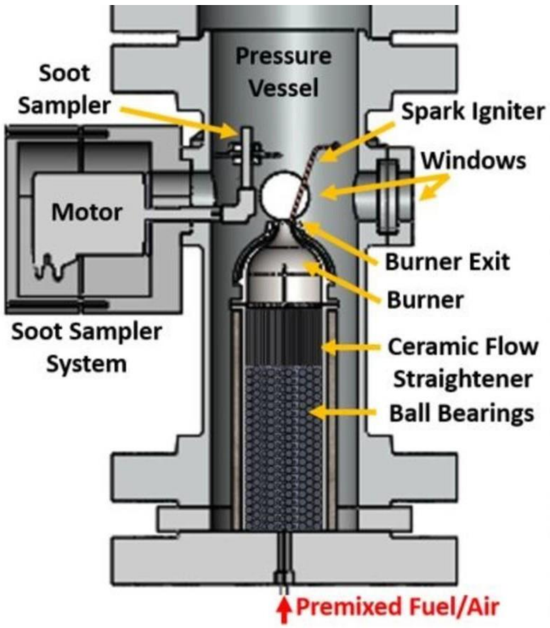
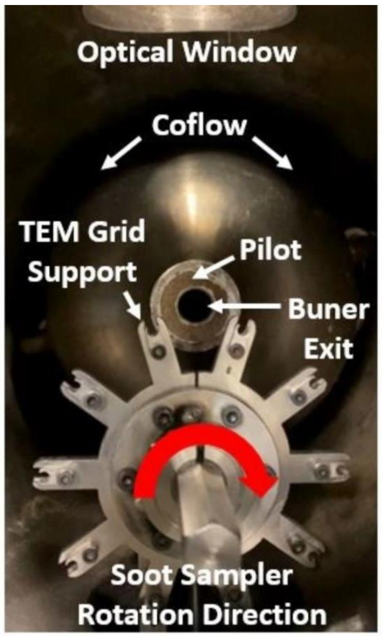
LII Calibration Burner

- Experiments conducted on a laminar flame burner (LFB) test rig
- LFB burned premixtures of prevaporized Jet A and air
  - Methane and air pilot flame with nitrogen co-flow
- Flow metering achieved with custom designed gas control panel and vaporization panel
  - Gas flow controlled by manual regulators and metered by calibrated orifices
  - Fuel tank pressurized with nitrogen to force liquid through calibrated rotameter into vaporizer
  - Vaporized fuel and air mixture sent through heated lines to LFB
- Thermophoretic soot sampler system built to extract soot from flame





LII Modeling – Absorption and Radiation

- Energy conservation

$$\frac{dU_{internal}}{dt} = \dot{Q}_{Absorption} - \dot{Q}_{Conduction} - Q_{Radiation}$$

$$\frac{dU_{internal}}{dt} = \frac{\pi}{6} d^3 N_p \rho_s c_s \frac{dT}{dt}$$

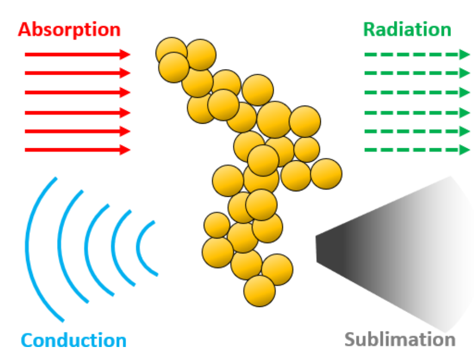
- Energy absorbed from laser incidence

$$\dot{Q}_{Absorption} = \frac{\pi^2 d^3 E(m) F_0 q(t) N_p}{\lambda}$$

- Energy lost due to radiation after particle heating

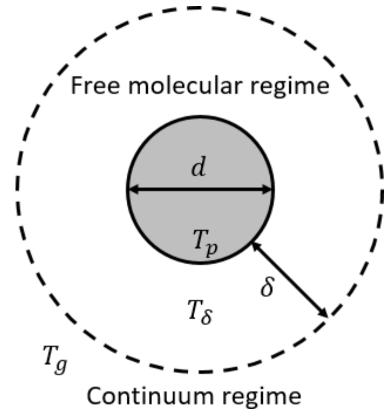
d	Primary particle size
N_p	Primary particles per aggregate
ρ_s	Soot density
c_s	Soot specific heat
$E(m)$	Refractive index function (0.4)
F_0	Laser fluence
$q(t)$	Laser temporal profile function
λ	Laser wavelength
T	Temperature
h	Planck constant
k_B	Boltzmann constant
c	Speed of light

$$\dot{Q}_{Radiation} = N_p \int_0^\infty \frac{8\pi^3 c^2 h}{\lambda^6} \frac{d^3 E(m)}{\exp\left(\frac{hc}{k_B \lambda T}\right) - 1} d\lambda = \frac{199\pi^3 d^3 (k_B T)^5 E(m) N_p}{h^4 c^3}$$



LII Modeling - Conduction

- At low pressure conditions, mean free path exceeds particle size, conduction occurs in free molecular regime
- At elevated pressures, conduction is in transition regime and the Fuchs method is used to approximate transition regime conduction
- The Fuchs method involves finding a limiting sphere radius and temperature
  - Inside the sphere, free molecular regime conduction is used in calculations
  - Outside the sphere, continuum regime conduction is used in calculations



- Free molecular regime conduction

$$\dot{Q}_{conduction} = \alpha \pi R_a^2 \frac{p_g}{2}\sqrt{\frac{8k_B T_\delta}{\pi m_g}}\,\frac{\gamma^* + 1}{\gamma^* - 1}\left(\frac{T}{T_\delta} - 1\right)$$

- Continuum regime conduction

$$\dot{Q}_{conduction} = 4\pi(\delta + R_a)\int_{T_g}^{T_\delta} k_g \, dT$$

- Average specific heat ratio

$$\frac{1}{\gamma^* - 1} = \frac{1}{T - T_\delta}\int_{T_\delta}^{T} \frac{1}{\gamma - 1}\, dT$$

p_g	Ambient gas pressure
m_g	Mass of gas molecule
T_δ	Limiting sphere temperature
α	Soot thermal accommodation coefficient
R_a	Radius of equivalent sphere based on aggregate projected area
f_a	Aggregate projected area prefactor (1.1)
ε_a	Aggregate projected area exponent (1.08)
γ^*	Average specific heat ratio of gas
δ	Limiting sphere boundary layer thickness
k_g	Conduction coefficient of gas
T_g	Ambient gas temperature

Model Calibration in Laminar Premixed Combustor

- To validate the model, we generated a particle-size-to-time-constant library at different pressures
- Fit to LII measurements in a Jet A flame in a laminar premixed combustor
- Conducted extractive soot particle sizing with TEM grids
- Compared simultaneous soot particle sizing with LII model results showing good match in soot particle size distribution
- Care must be taken to estimate parameters properly, including N_p (number of primary particles per aggregate), T_g (bath gas temperature), and $E(m)$ (refractive index) and α (absorption)