Understanding Transient Combustion Phenomena in Low-NO_x Gas Turbines

Project DE-FE0025495, Oct. 2015 – Sept. 2018
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Overview of presentation

- Project motivation and approach
- Year 1 Results:
  - Steady-state fuel staging – mechanisms for instability suppression
  - Transient fuel staging – natural system timescales
- Conclusions and next steps

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Objective of the program is to *understand, quantify,* and *predict* combustion instability during ***transient operation***

- Two major deliverables for the program:

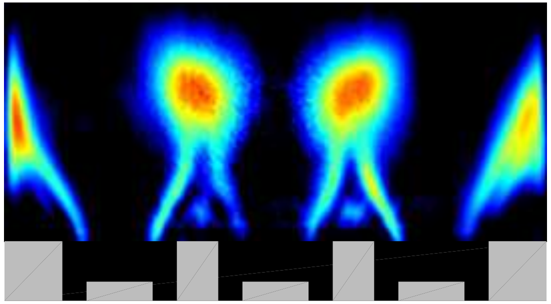
  1. Fundamental understanding of flow and flame behavior during combustion transients and mechanisms for transition to instability

  2. Development of a stability prediction or quantification framework

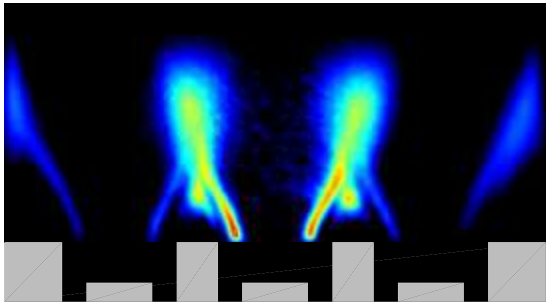
Three types of transients will be considered in the program that mimic the types of transients used in operational turbines

Fuel Splitting

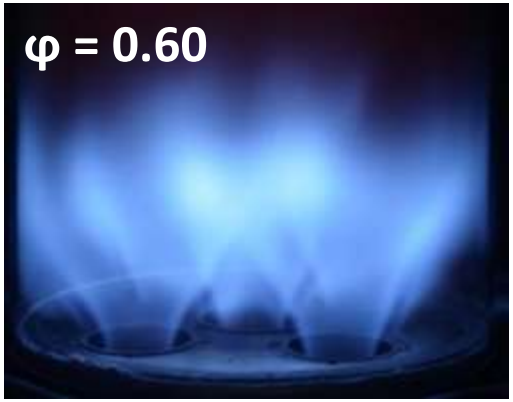
ϕ = 0.65 in all nozzles



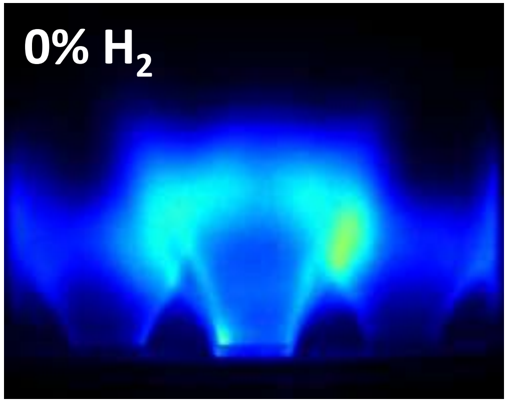
ϕ = 0.67 in outer nozzles,
ϕ = 0.82 in middle nozzle

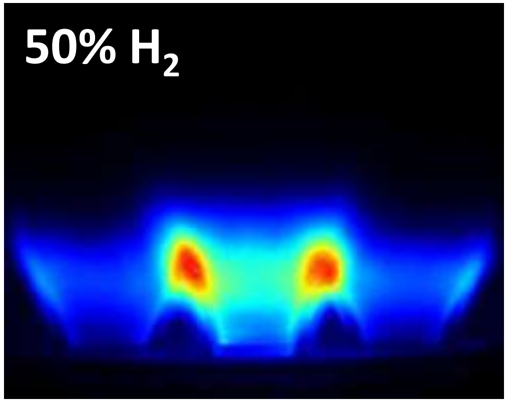


Equivalence Ratio



Fuel Composition

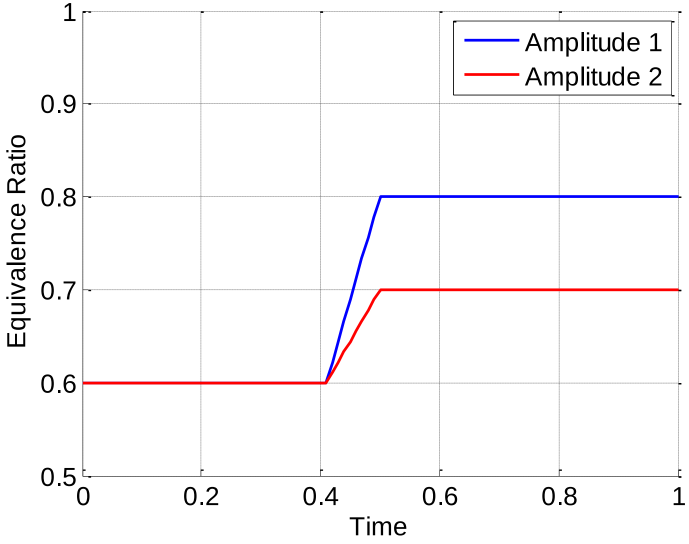




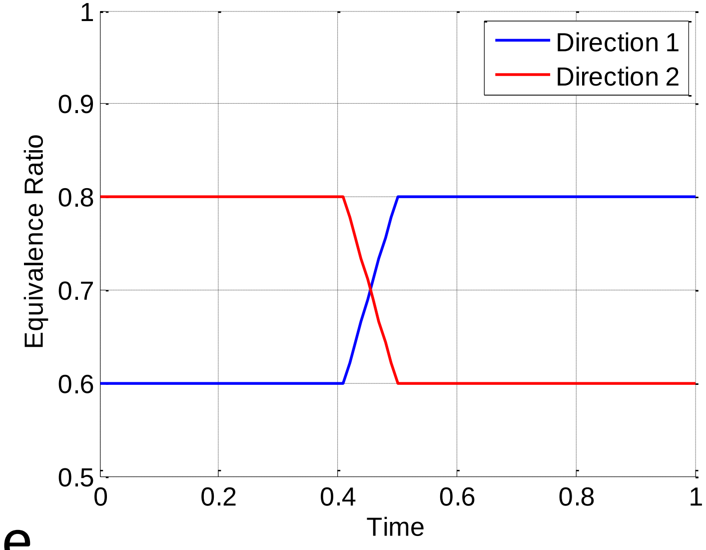
Images obtained from work done
by Alex De Rosa (2011)

The transients will be quantified using three different metrics: *amplitude*, *timescale*, and *direction*

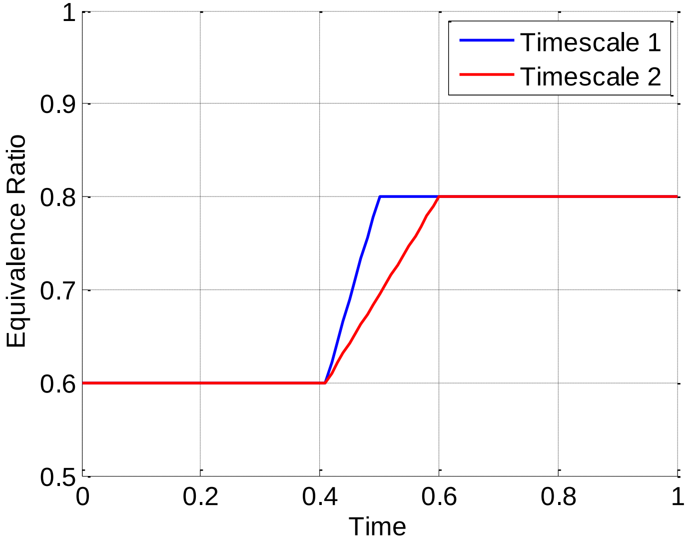
Amplitude



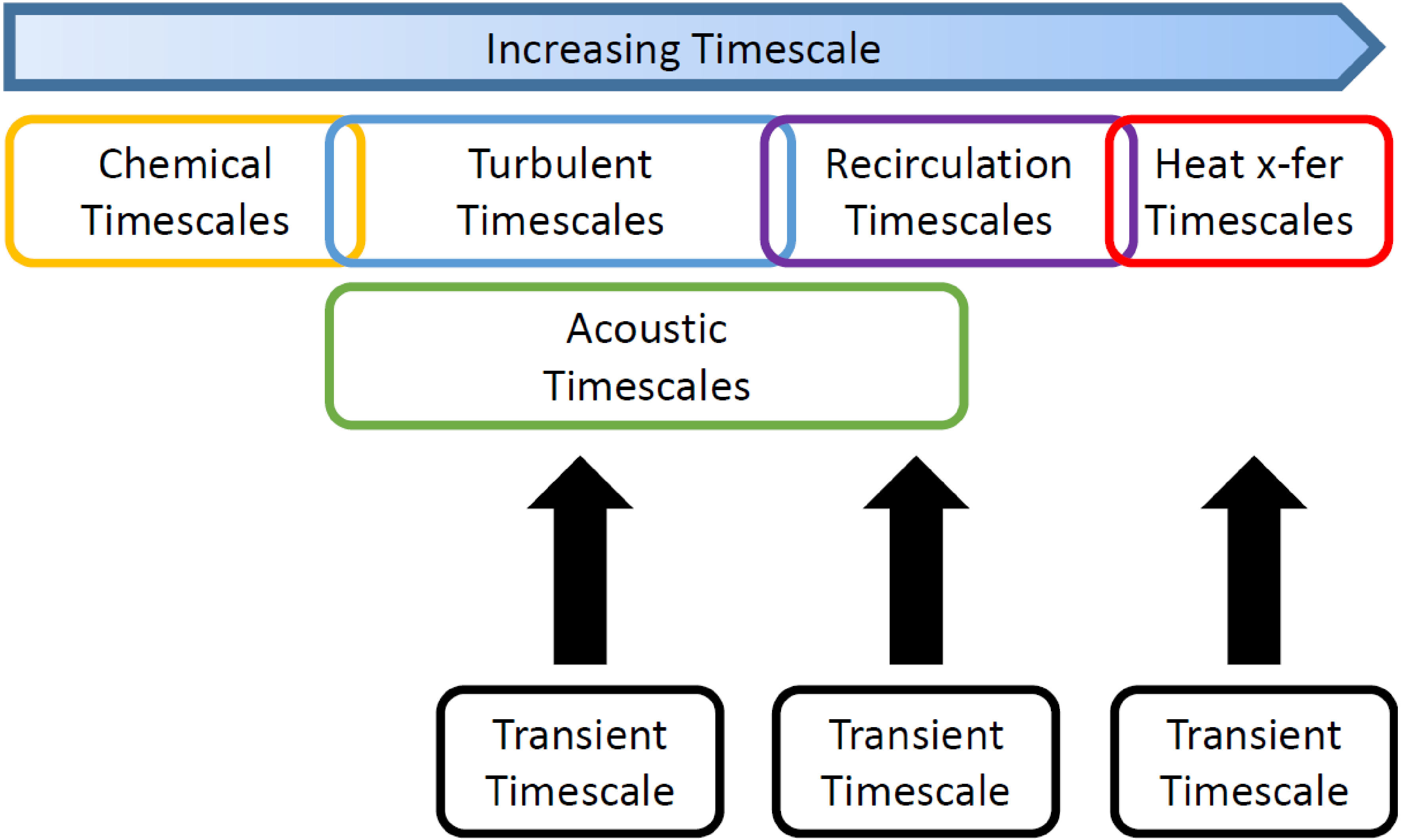
Direction



Timescale



Varying the transient timescales allows for different processes to equilibrate during the transient, changing the path



Increasing Timescale

Chemical Timescales

Turbulent Timescales

Recirculation Timescales

Heat x-fer Timescales

Acoustic Timescales

Transient Timescale

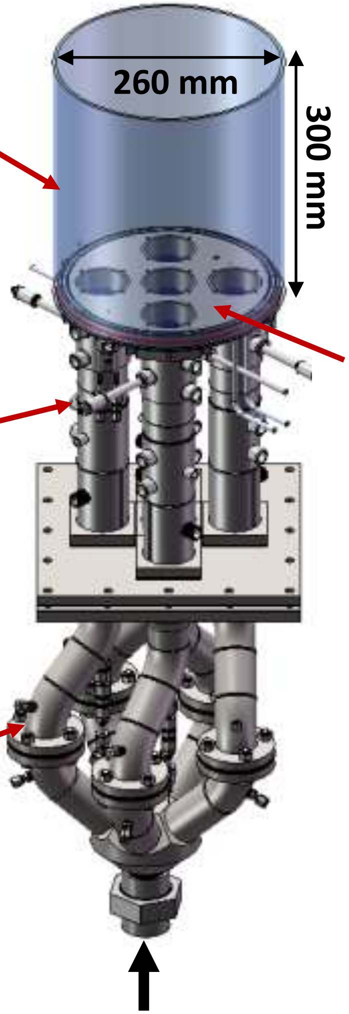
Transient Timescale

Transient Timescale

Project Management Plan – progress to date

- **Task 1** – Project management and planning
- **Task 2** – Modification of current experimental facility with monitoring diagnostics and new hardware for transient control
- **Task 3** – Map combustor timescales at target operating points
- **Task 4** – Design of transient experiments
- **Task 5** – Fuel split transients (multi-nozzle combustor)
- **Task 6** – Equivalence ratio transients (single- and multi-nozzle)
- **Task 7** – Fuel composition transients (single- and multi-nozzle)
- **Task 8** – Data analysis and determination of prediction/quantification framework

Experimental facilities include both a single-nozzle and multi-nozzle combustor, fuel splitting on multi-nozzle only



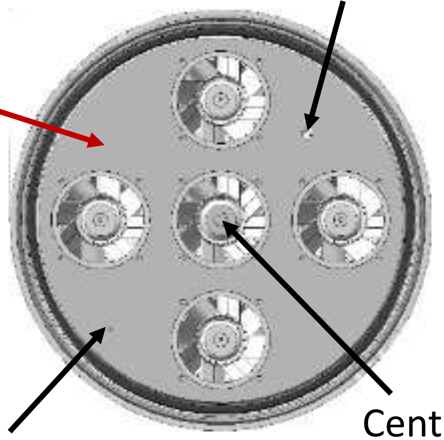
Combustor Can

Five Swirled Nozzles

Manifold

Premixed NG-air mixture

Dump plate

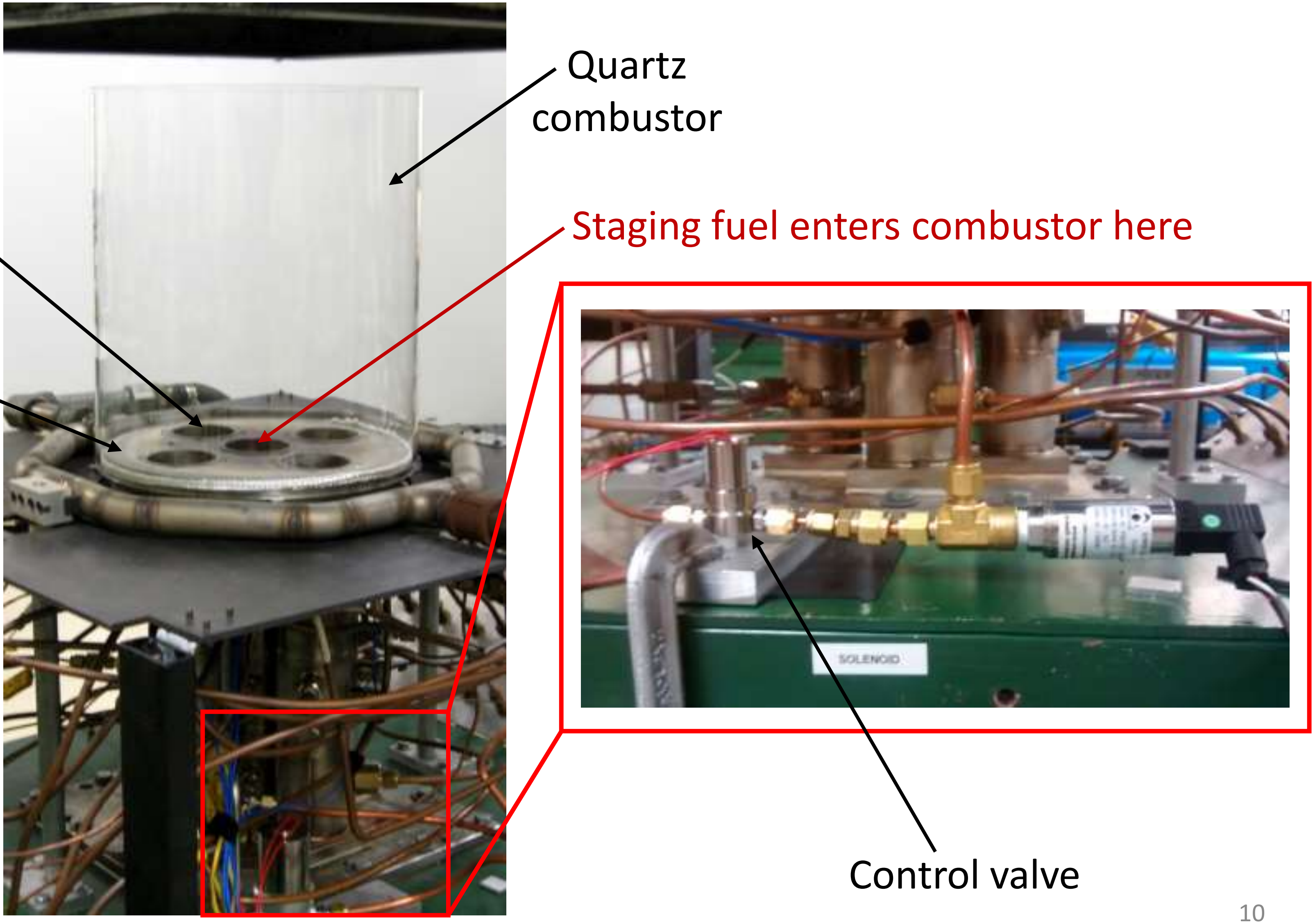


Dump plate metal temperature
(K-type thermocouple)

Combustor pressure fluctuation
(PCB pressure transducer)

Centerbody metal temperature
(K-type thermocouple)

TASK 2: Hardware modification focused on a valve with linear actuation to control fuel flow transients for fuel-splitting studies



Quartz combustor

Five nozzles

Dump plate

Staging fuel enters combustor here

Control valve

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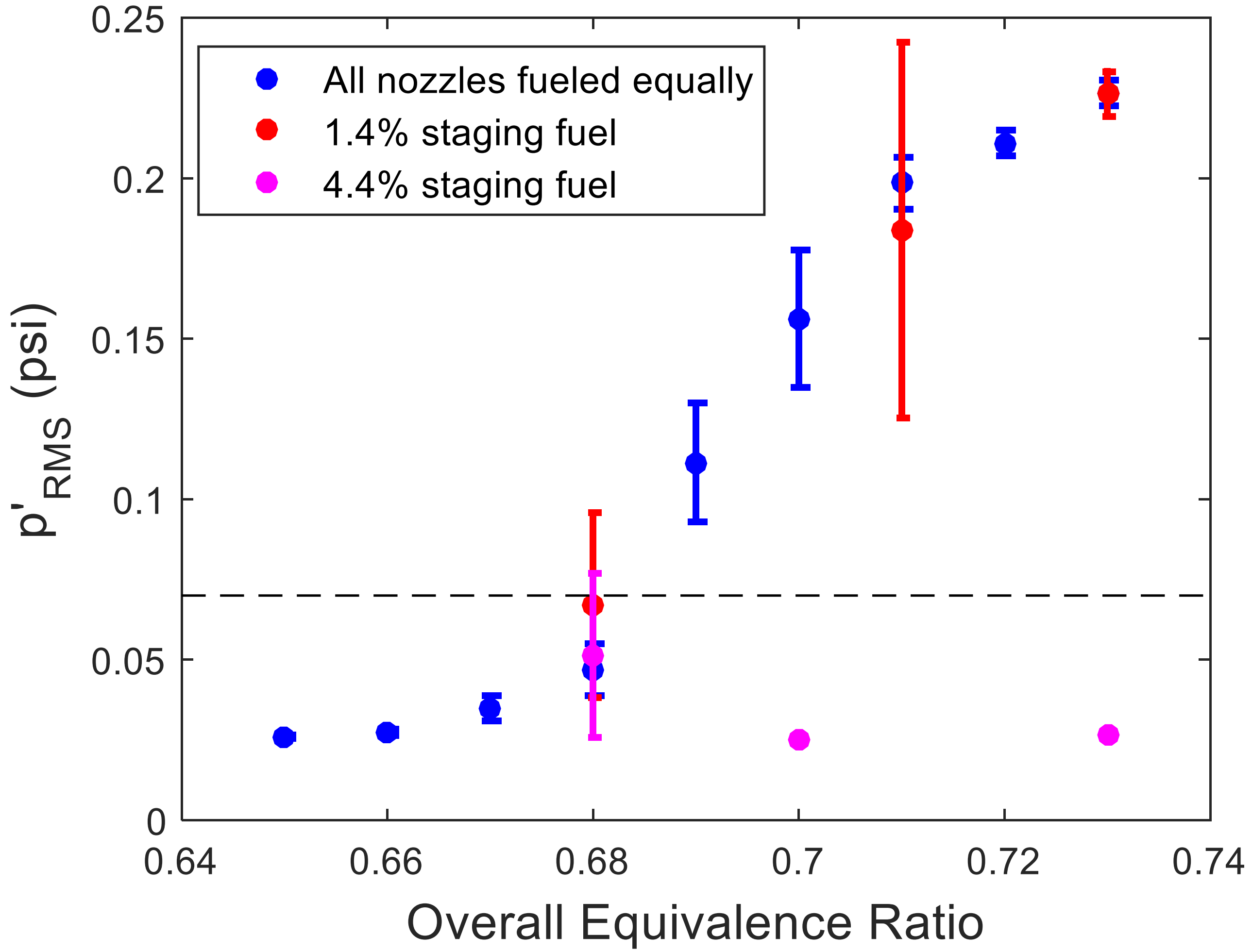
In line with industry experience, we have shown that fuel staging suppresses instability in a multi-nozzle combustor

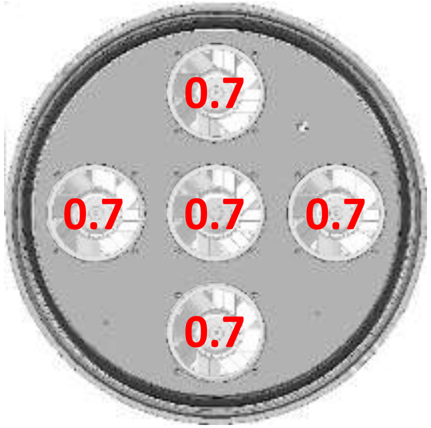


TASK 3: Test matrix was developed to measure the effect of fuel splitting and quantify repeatability, a key technical challenge

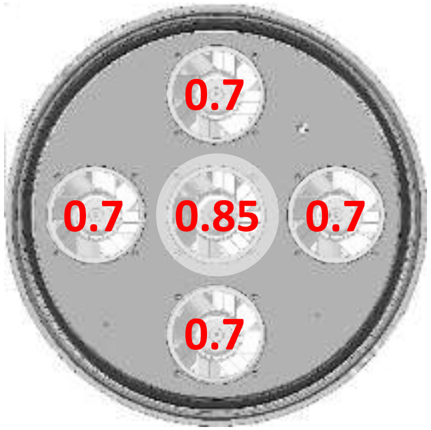
Test Case 1 – Varying Global ϕ

- ϕ_{center} increases to suppress instability
- ϕ_{outer} remains constant
- ϕ_{global} varies

Unstable:



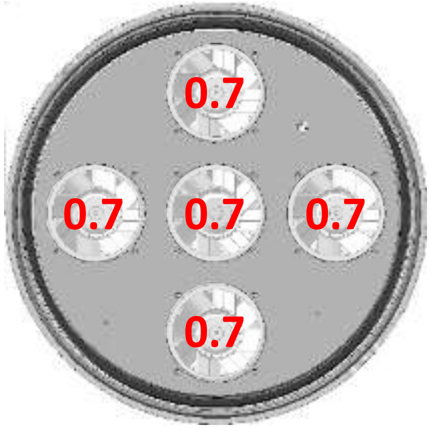
Stable:



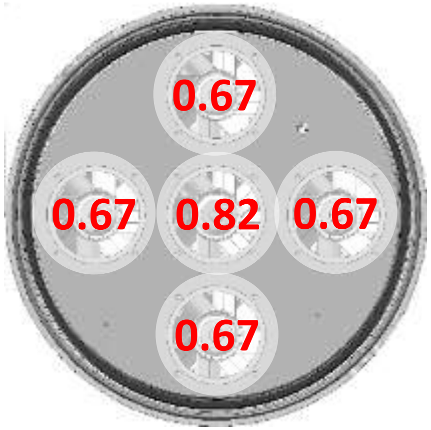
Test Case 2 – Constant Global ϕ

- ϕ_{center} increases to suppress instability
- ϕ_{outer} decreases
- ϕ_{global} is constant

Unstable:



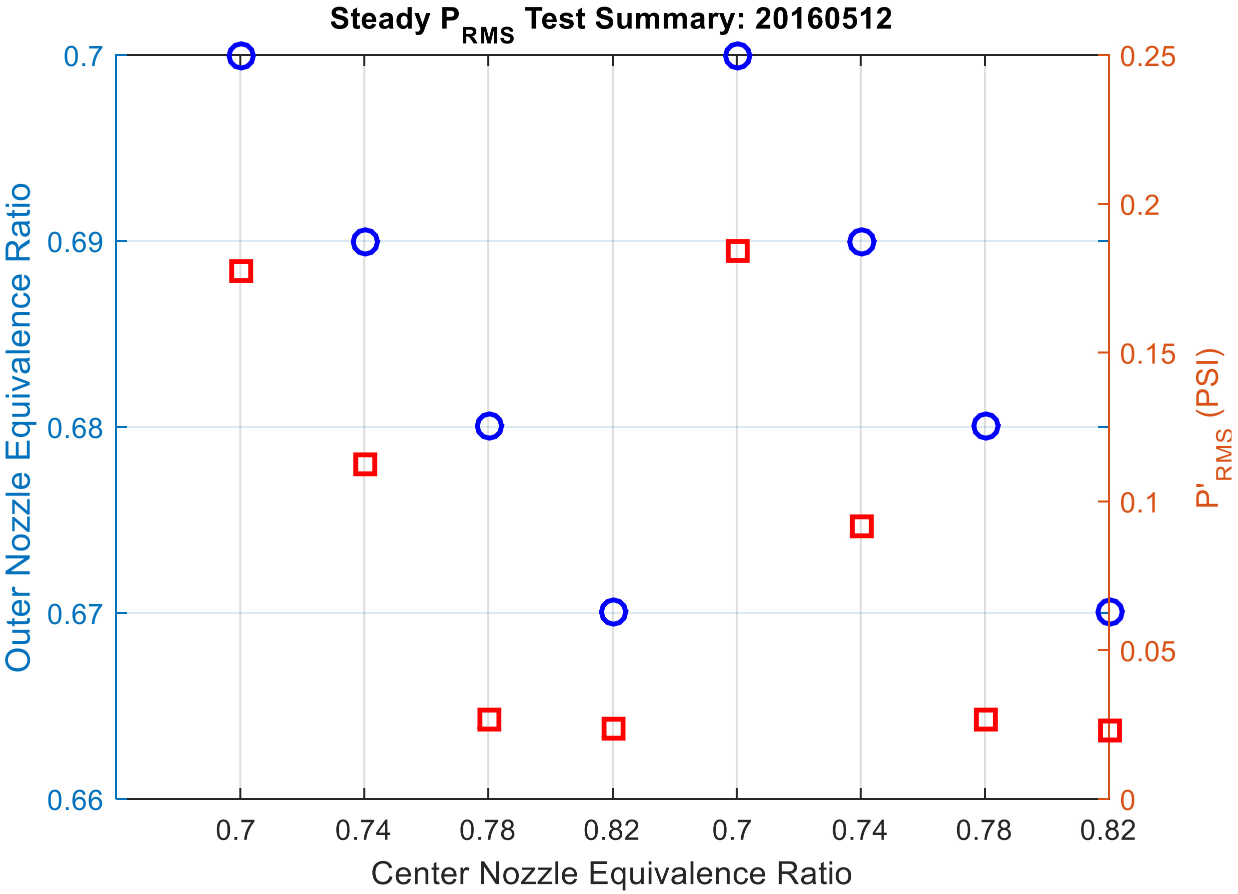
Stable:



Fuel staging was found to be able to suppress combustion instability when fuel flow is increased to middle nozzle

Test Case 2 – Constant Global ϕ

- ϕ_{center} increases to suppress instability
- ϕ_{outer} decreases
- ϕ_{global} is constant



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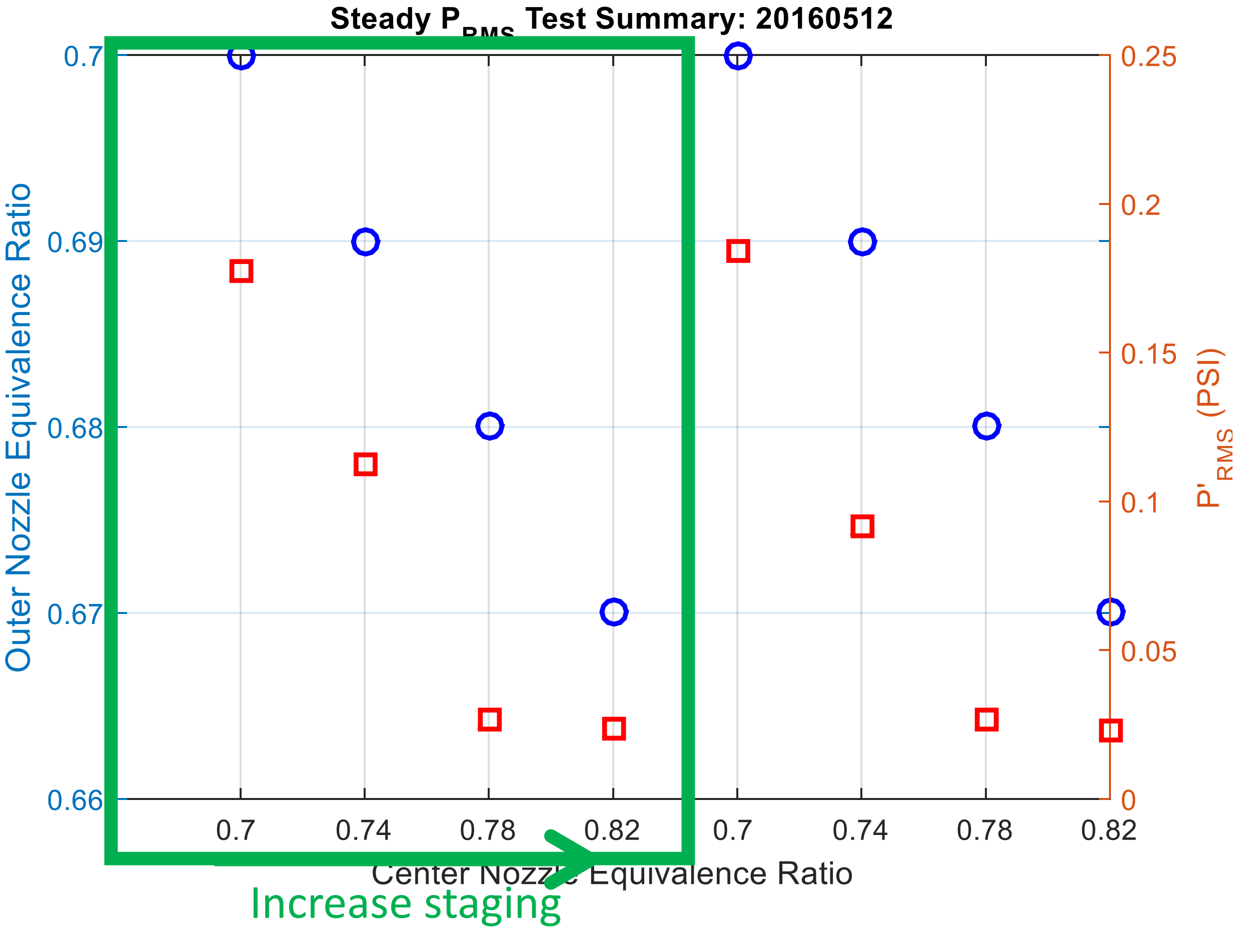

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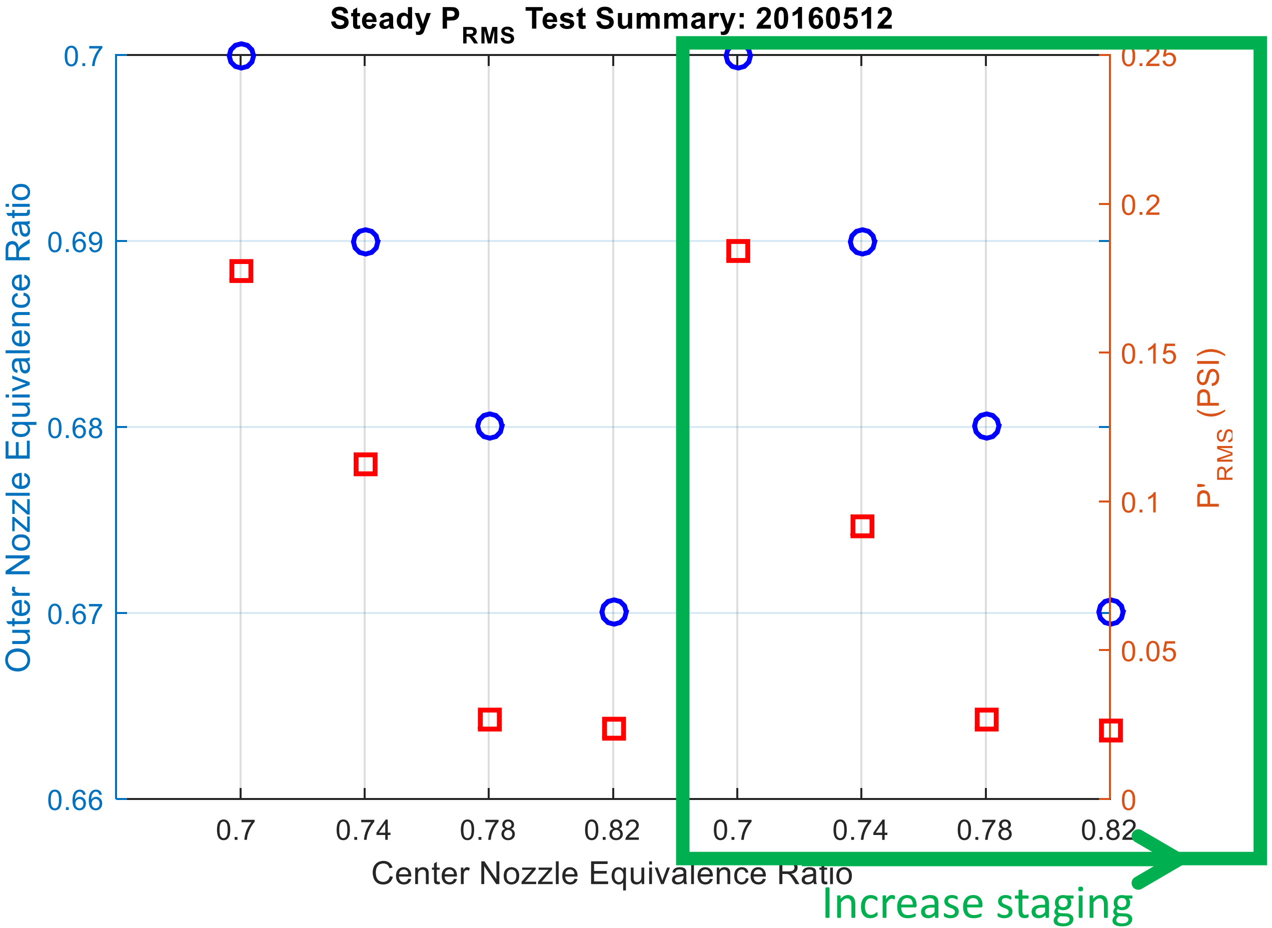

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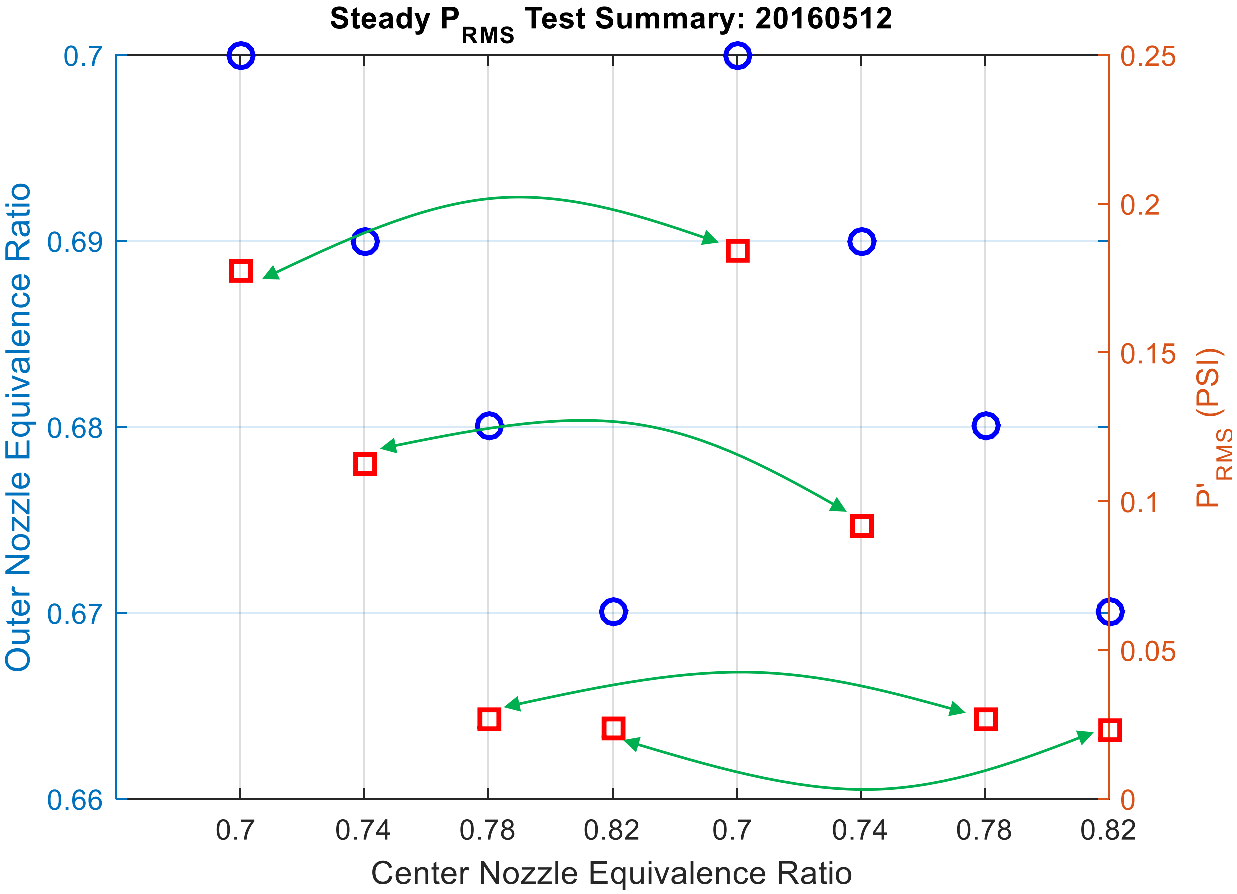
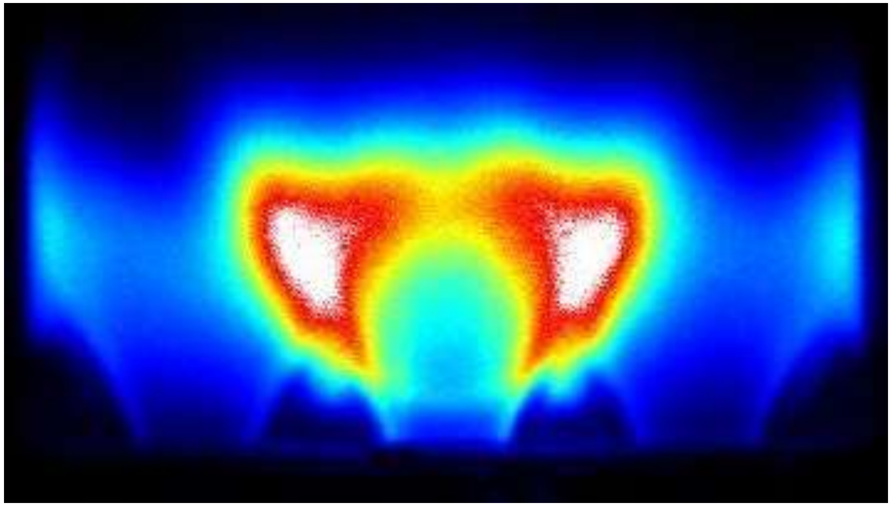


CH* chemiluminescence images are used to characterize flame structure, fluctuation, and phase

Images are obtained using a high-speed camera fitted with an intensifier

Line-of-sight photograph of multi-nozzle flame



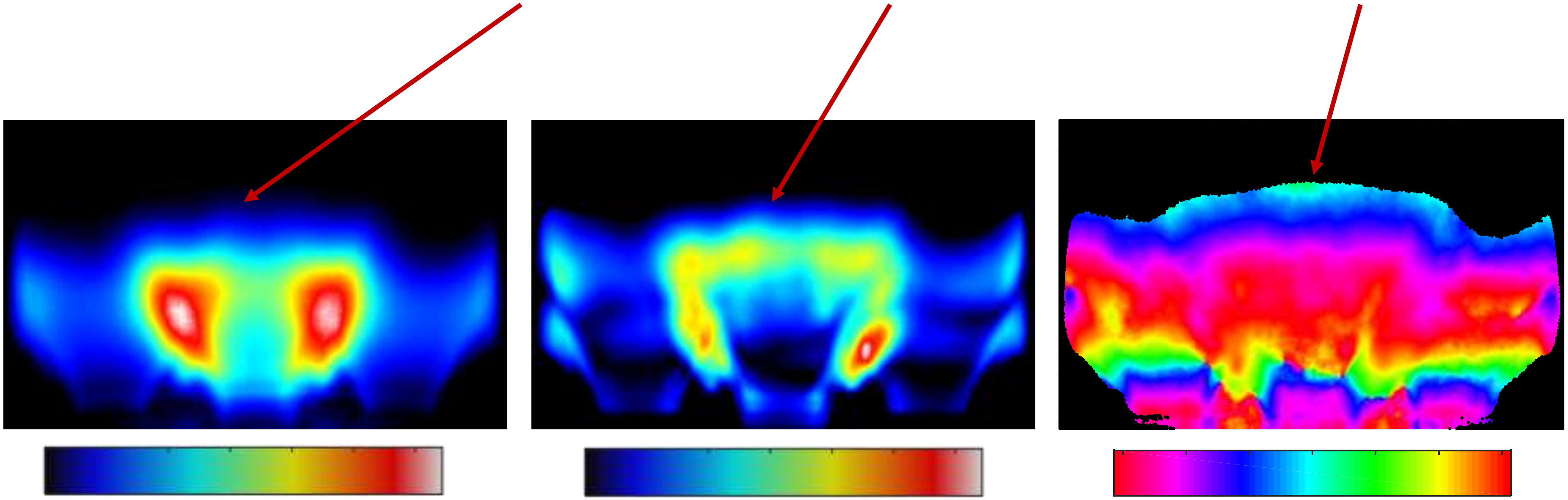
Line-of-sight CH* chemiluminescence image of multi-nozzle flame

Pseudo color map is applied to chemiluminescence images

One second of high speed data is obtained at 4000 frames per second

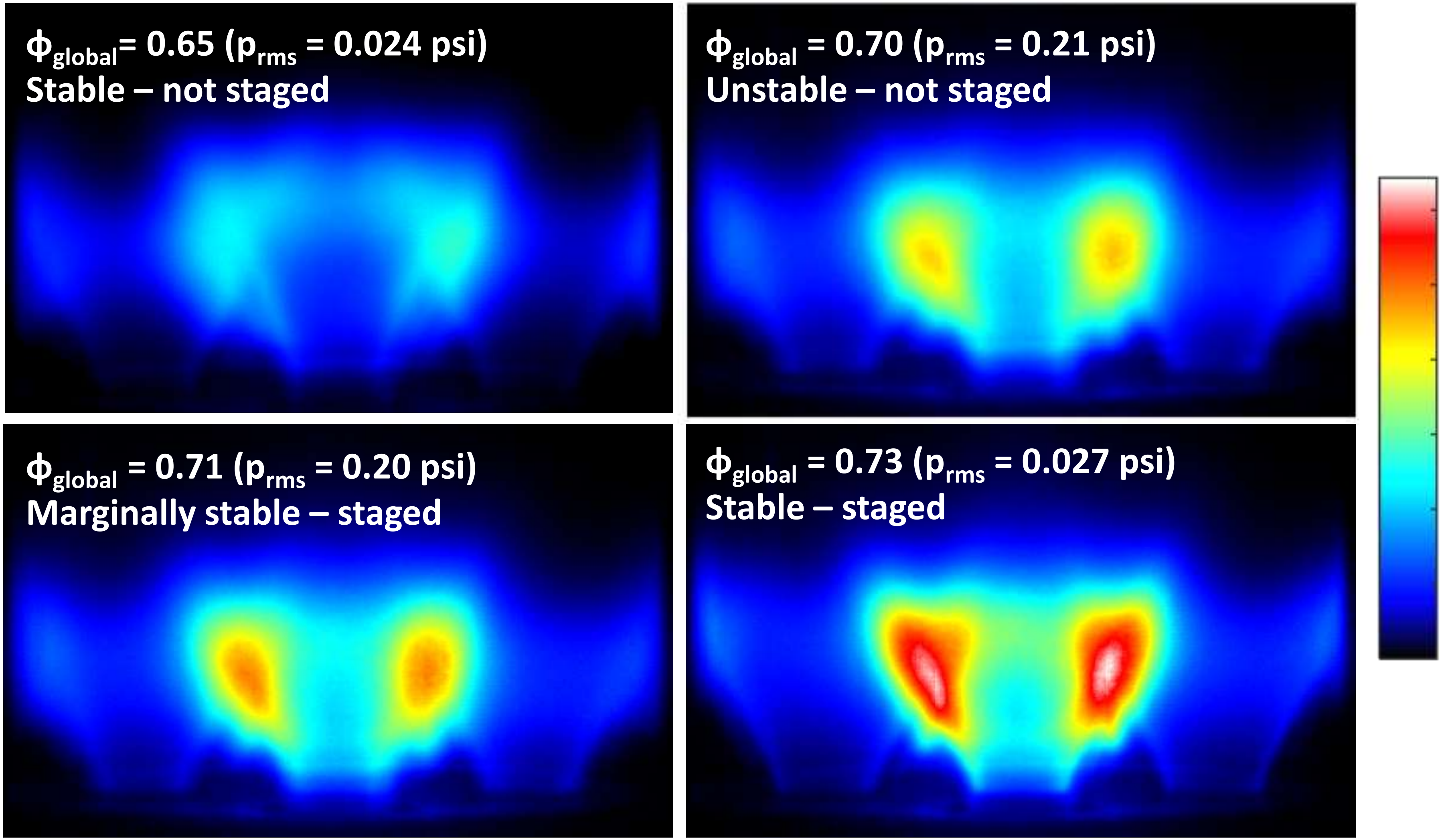
Images of forced flames can be decomposed into mean, RMS and phase components to understand instability mechanisms

$$Filtered\ Image = \boldsymbol{Mean\ Image} + \sqrt{2} * \boldsymbol{RMS\ Image} * \cos(2\pi f t + \boldsymbol{Phase\ Image})$$



Mean, RMS, and phase images are analyzed at different test conditions to determine the effects of fuel staging on time-averaged and phase-averaged flame structure

Flame structure does not change significantly with additional staging, though center flame has higher heat release



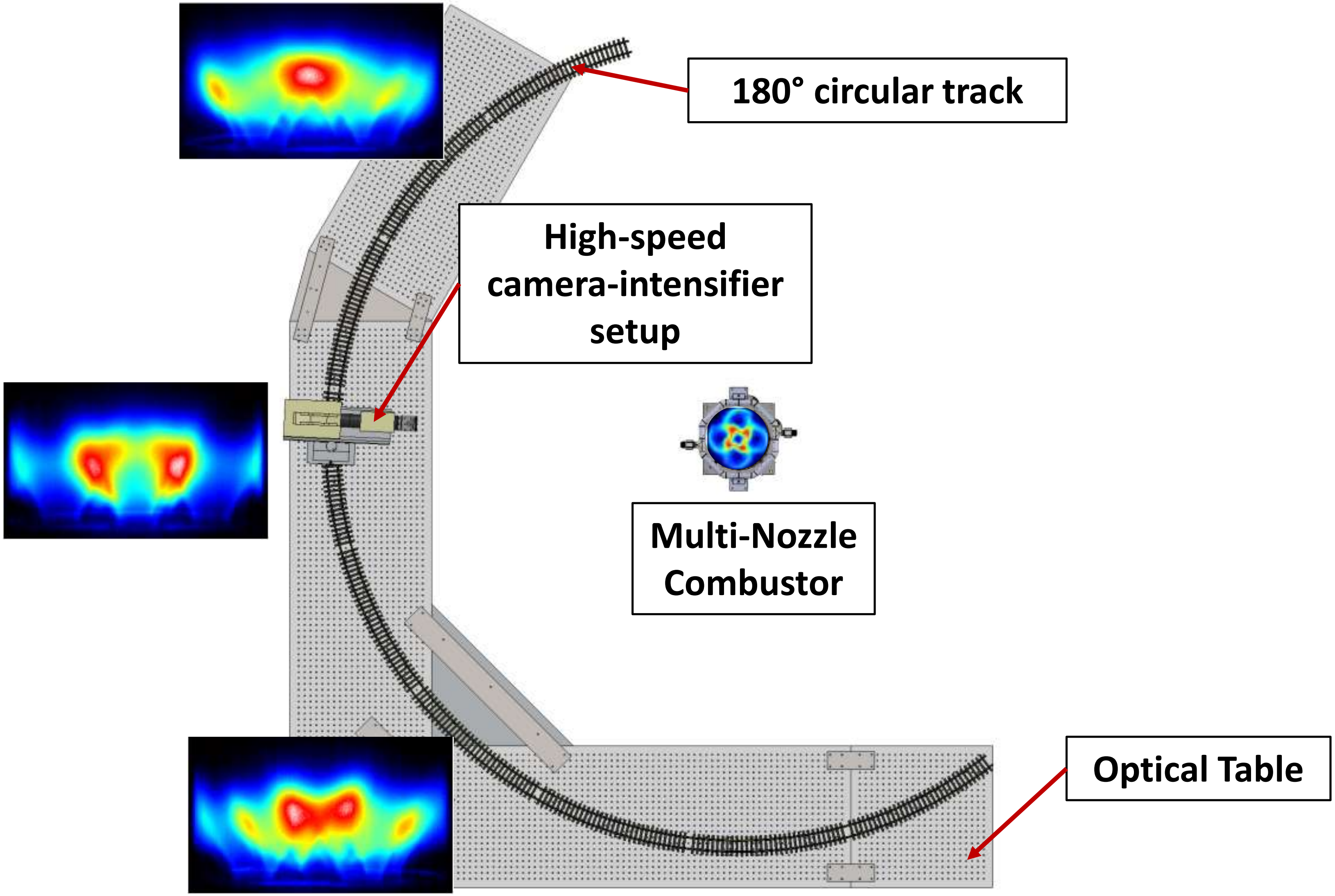
ϕ_{global} = 0.65 (p_{rms} = 0.024 psi)
Stable – not staged

ϕ_{global} = 0.70 (p_{rms} = 0.21 psi)
Unstable – not staged

ϕ_{global} = 0.71 (p_{rms} = 0.20 psi)
Marginally stable – staged

ϕ_{global} = 0.73 (p_{rms} = 0.027 psi)
Stable – staged

Line-of-sight chemiluminescence images are acquired at 5° increments around the combustor to create tomographic image



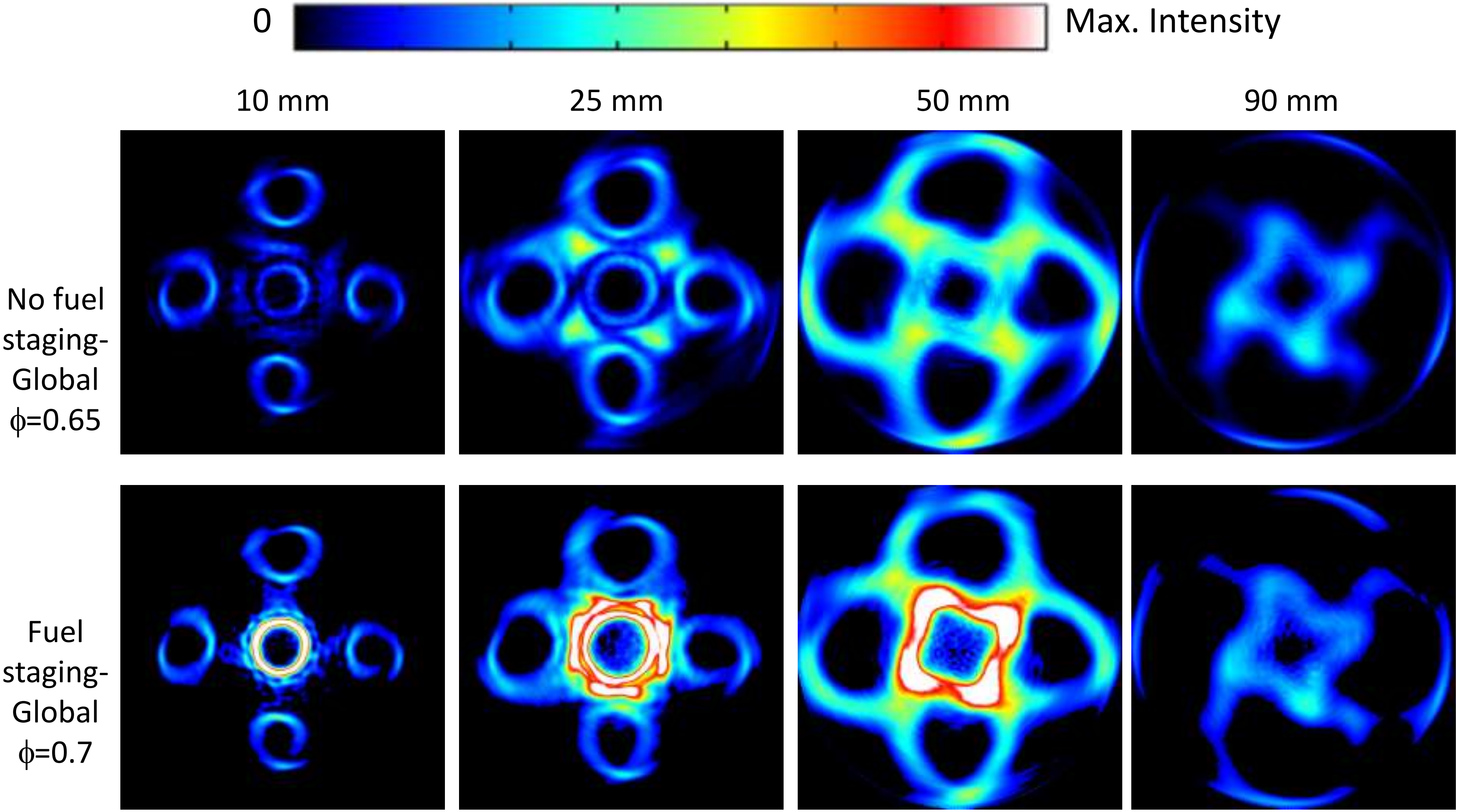
180° circular track

High-speed camera-intensifier setup

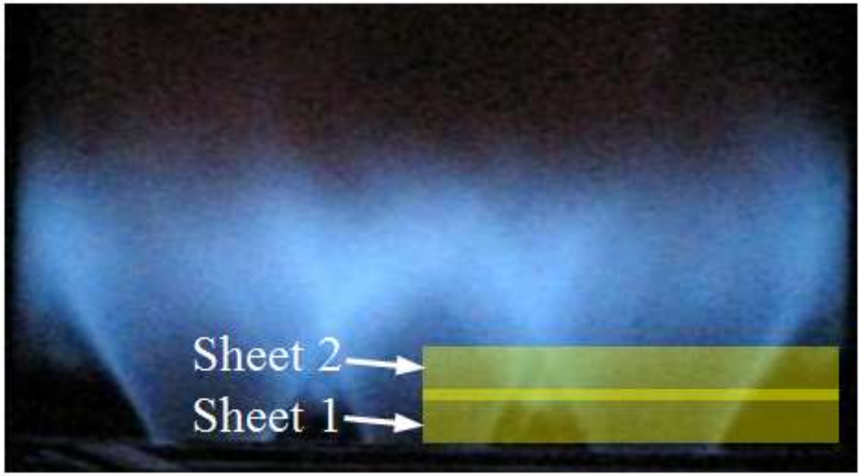
Multi-Nozzle Combustor

Optical Table

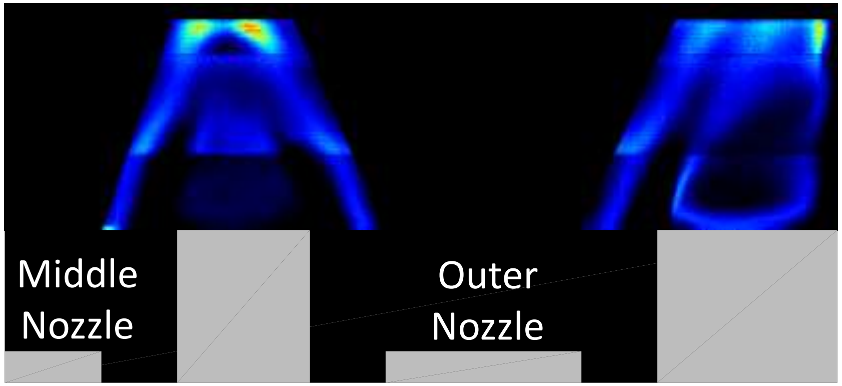
Different flame structures are observed between stable un-staged and stable staged cases through tomographic imaging



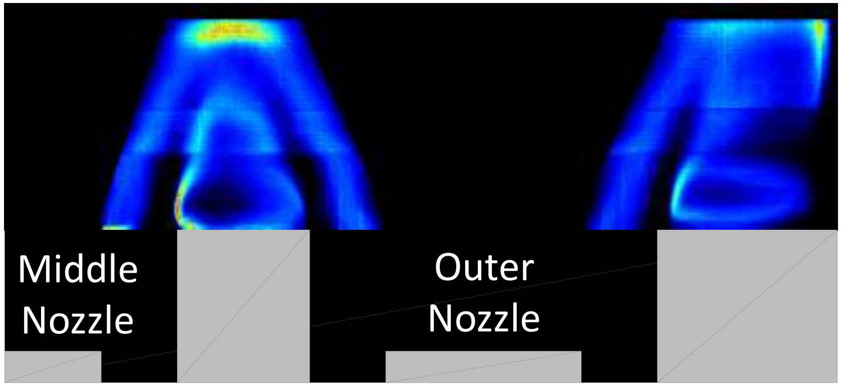
OH-PLIF imaging of the interaction region during staged cases shows instantaneous oscillations of the flame with staging



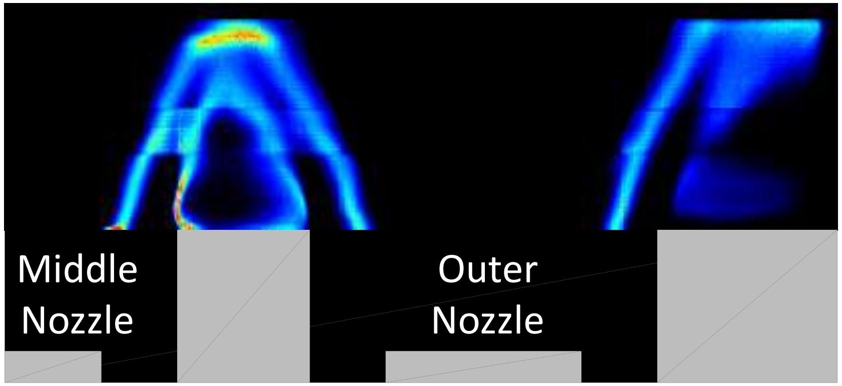
$\phi = 0.65$, stable – unstaged



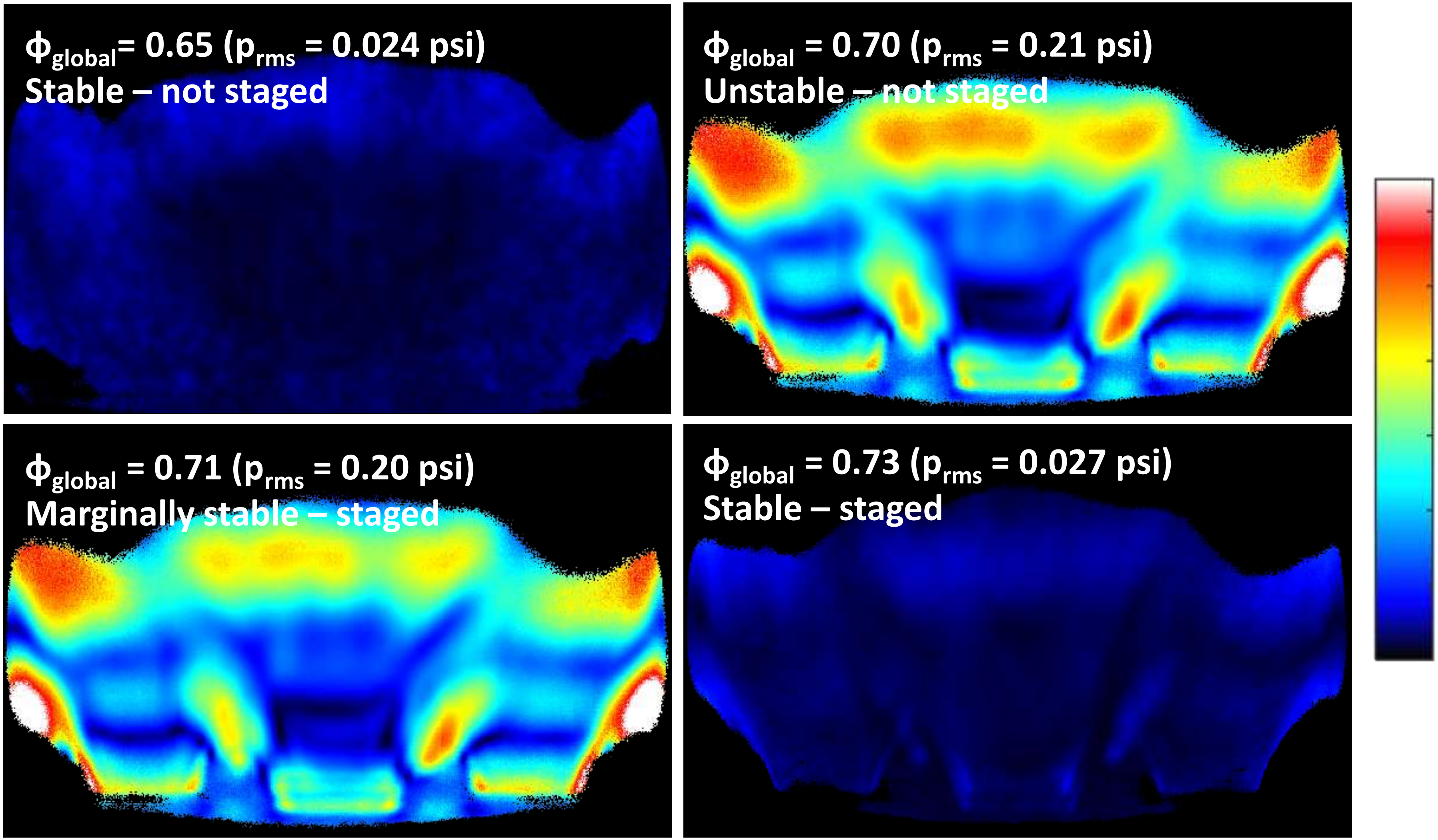
$\phi = 0.70$, unstable – unstaged



Staged - $\phi_{outer} = 0.70$, $\phi_{middle} = 0.85$



Heat release rate RMS levels are suppressed with staging, though signature is visible even at highest staging amount



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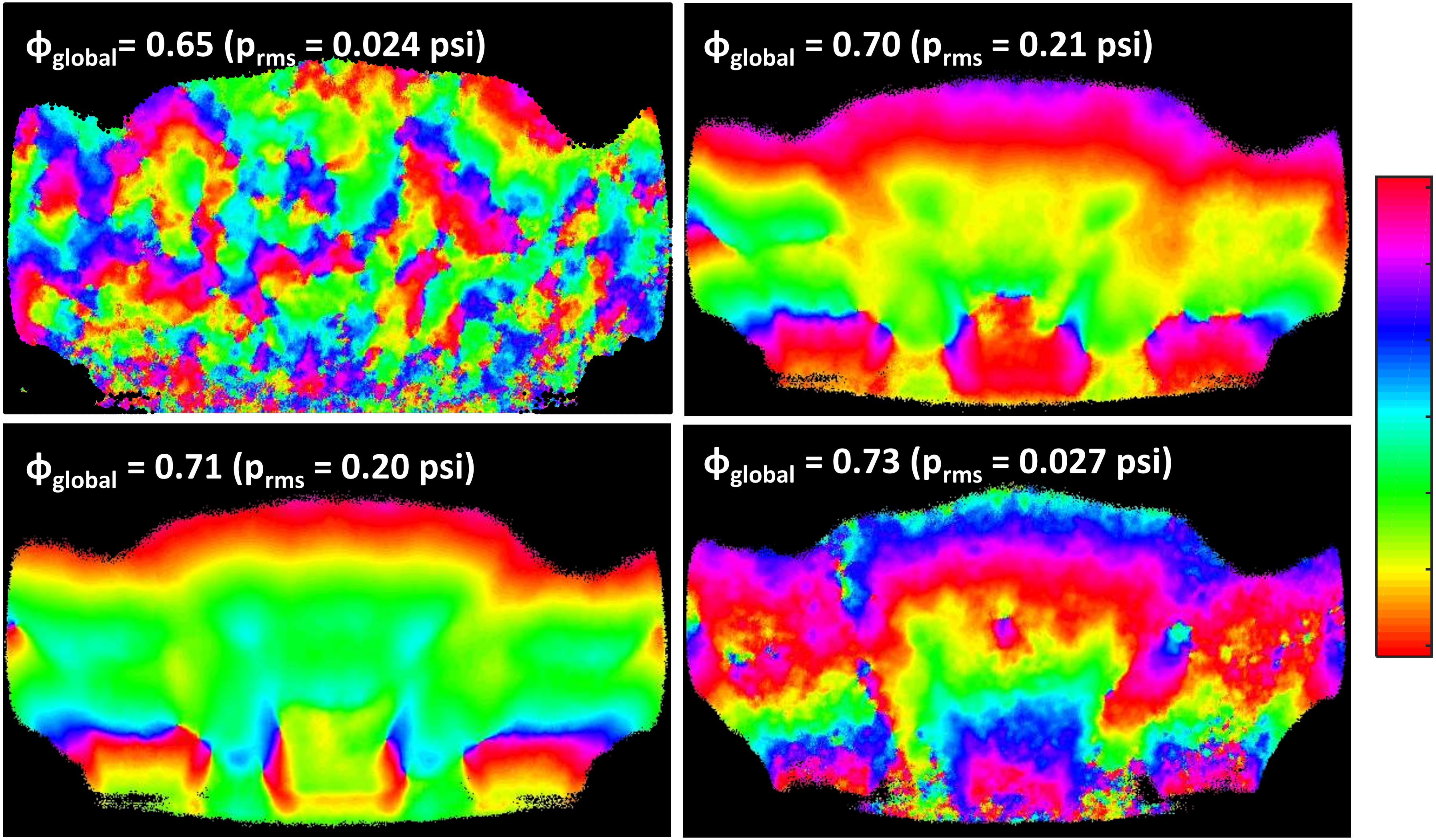
Marginally stable – staged

ϕ_{global} = 0.73 (p_{rms} = 0.027 psi)
Stable – staged

Phase of oscillations seems to indicate phase shift in oscillations during staging, possible suppression mechanism



ϕ_{global}= 0.65 (p_{rms} = 0.024 psi)

ϕ_{global} = 0.70 (p_{rms} = 0.21 psi)

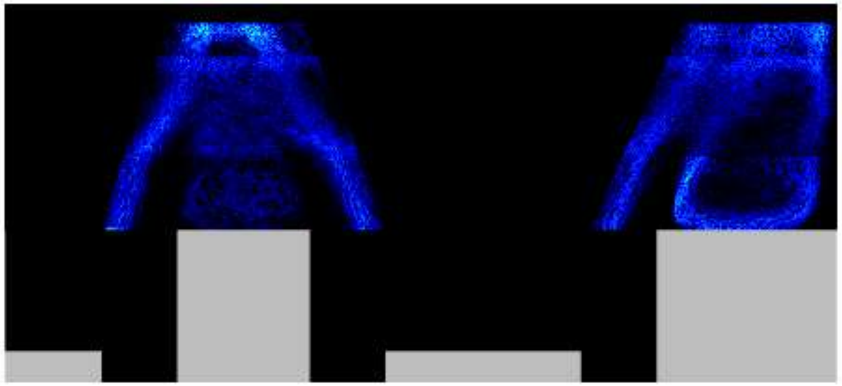
ϕ_{global} = 0.71 (p_{rms} = 0.20 psi)

ϕ_{global} = 0.73 (p_{rms} = 0.027 psi)

Differences in flame structure and the disturbances along the flame likely drive the phase-cancellation phenomenon

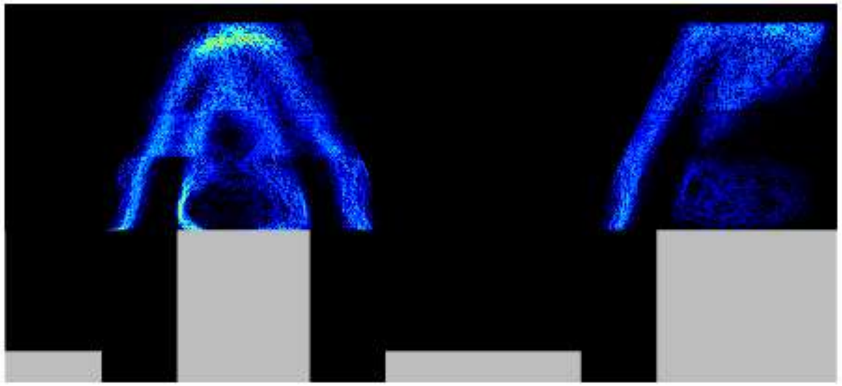
Stable – Unstaged

(ϕ=0.65)



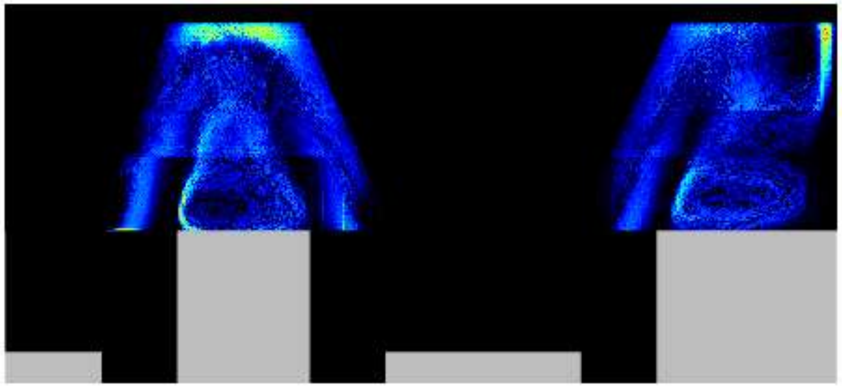
Stable – Staged

(ϕ_{outer} = 0.70, ϕ_{middle} = 0.85)



Unstable – Unstaged

(ϕ=0.70)



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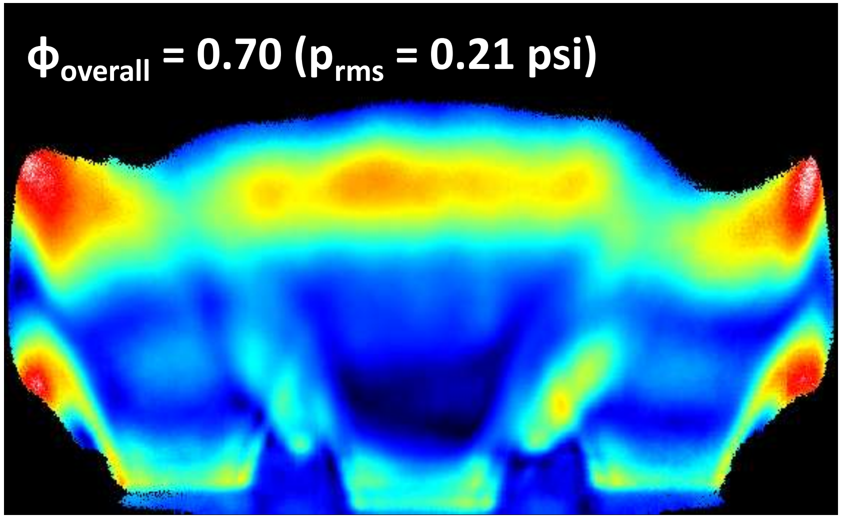
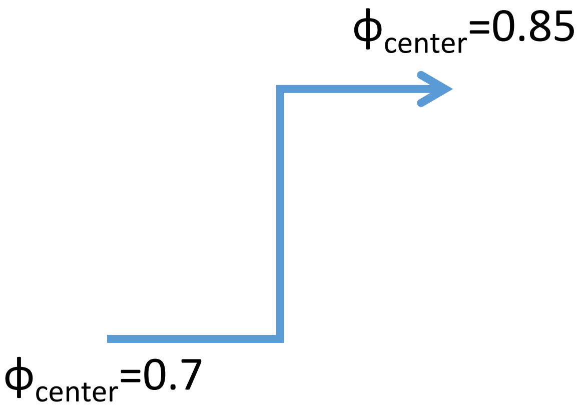
Task 4: Test matrix for initial transient testing considers step-change transients to determine natural time-scales of system



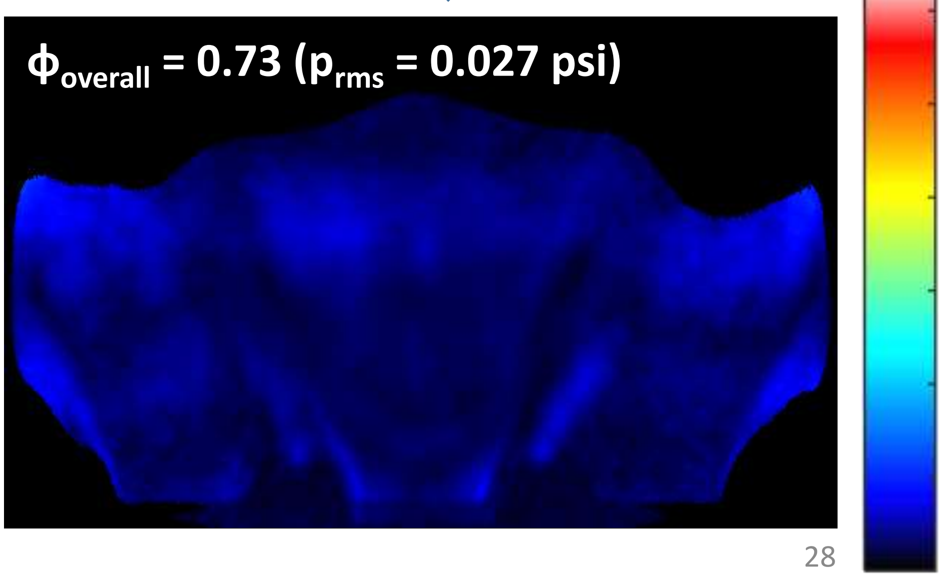
$\phi_{overall}$ = 0.70 (p_{rms} = 0.21 psi)



ϕ_{center}=0.85

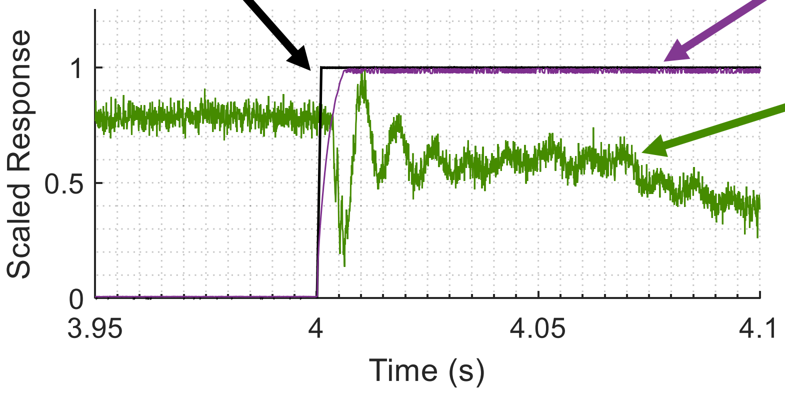
ϕ_{center}=0.7

<u>What is the time delay?</u>



$\phi_{overall}$ = 0.73 (p_{rms} = 0.027 psi)

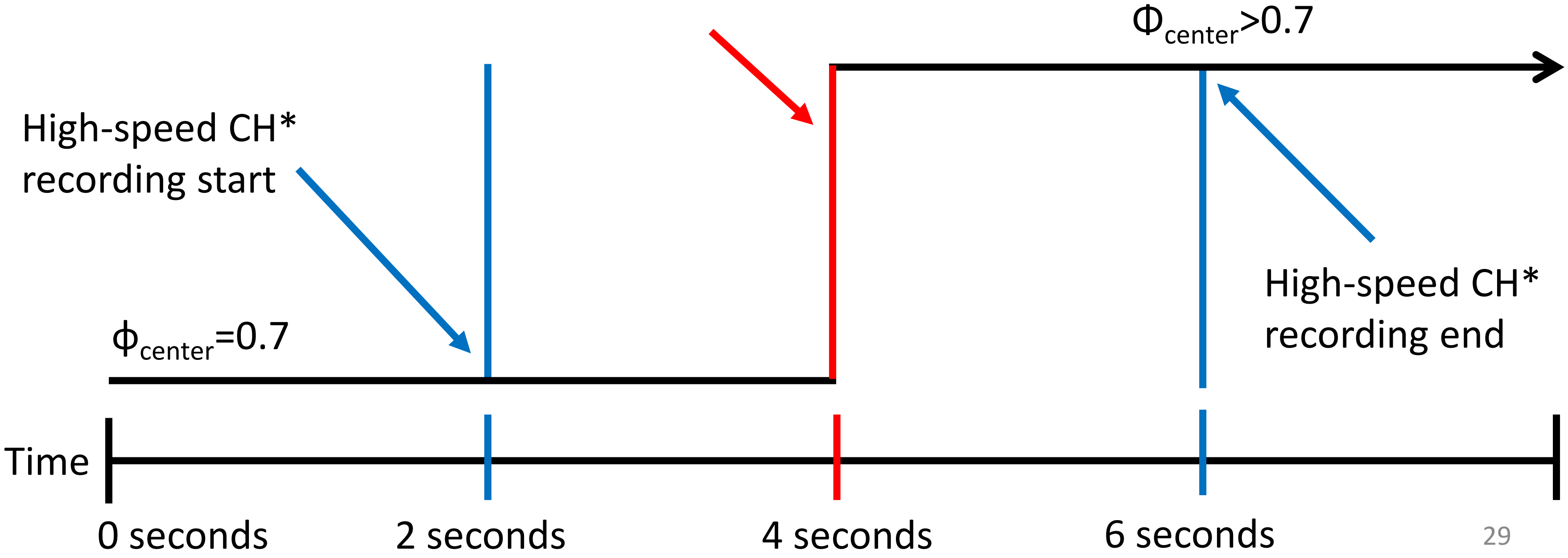
Impulse transients are executed using a fast-acting proportional control valve



Control Signal

Feedback Voltage

Scaled Valve Pressure Difference



$\Phi_{center}>0.7$

High-speed CH* recording start

$\phi_{center}=0.7$

High-speed CH* recording end

Time

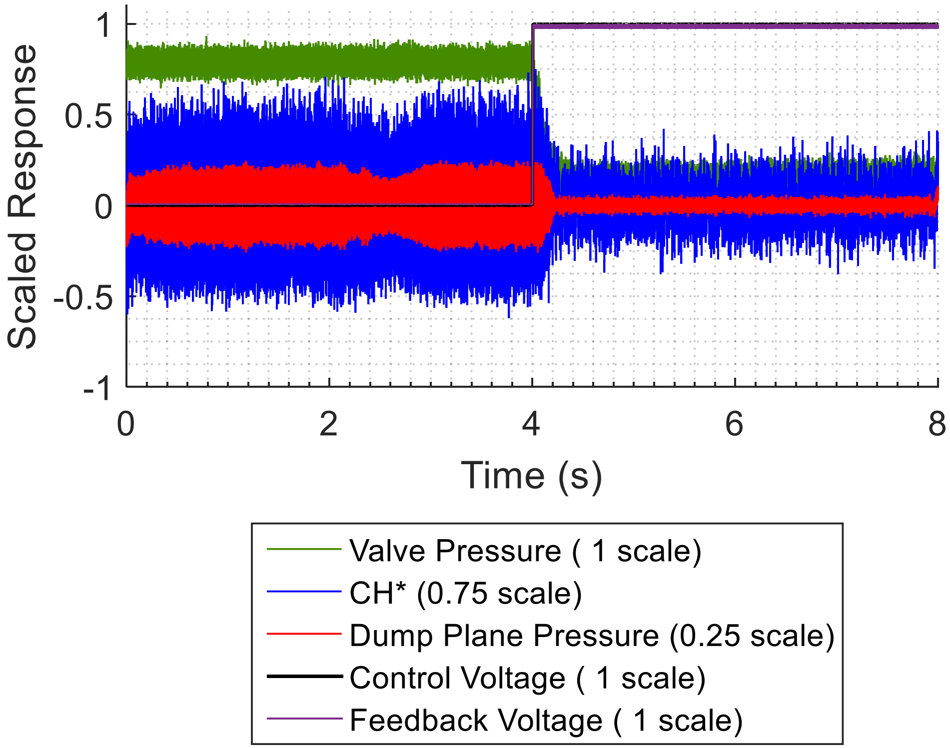
0 seconds

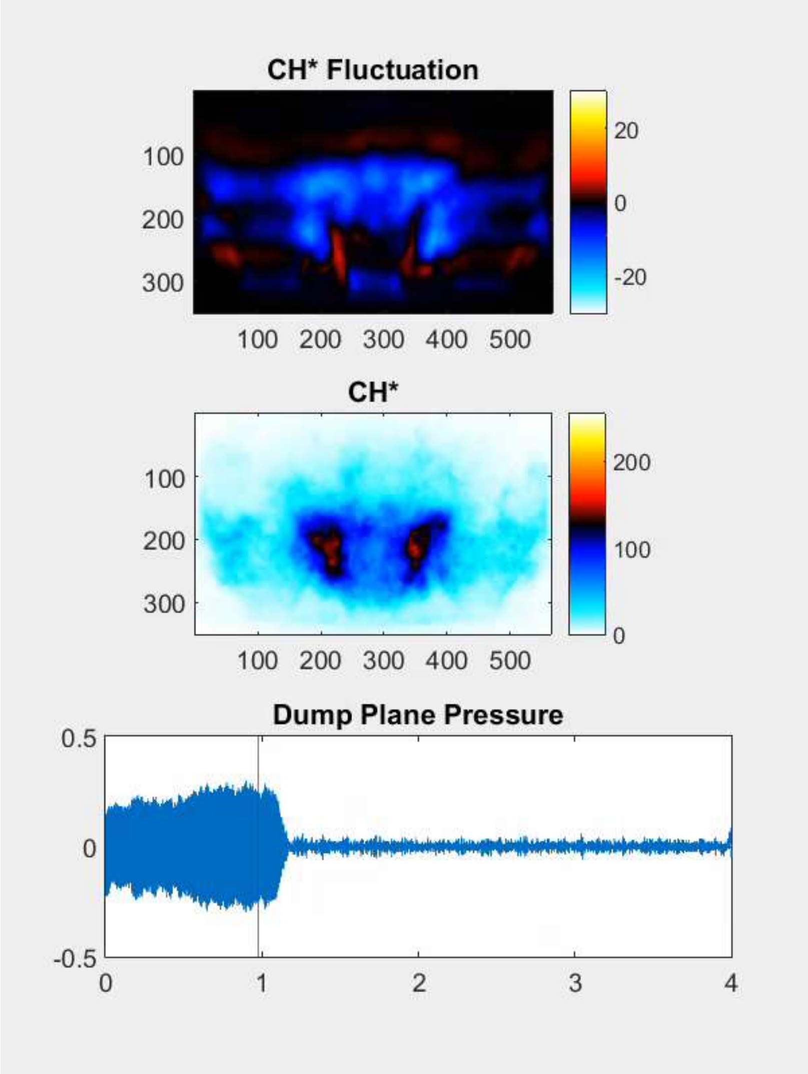
2 seconds

4 seconds

6 seconds

Both the fluctuation in CH* (blue) and pressure (red) track each other through the transient event.



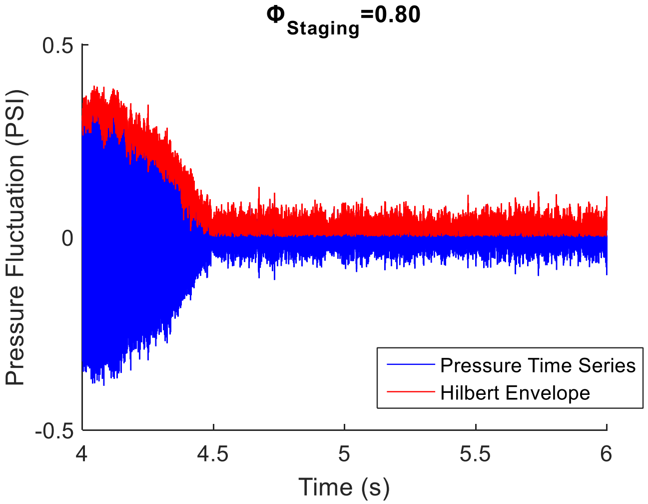


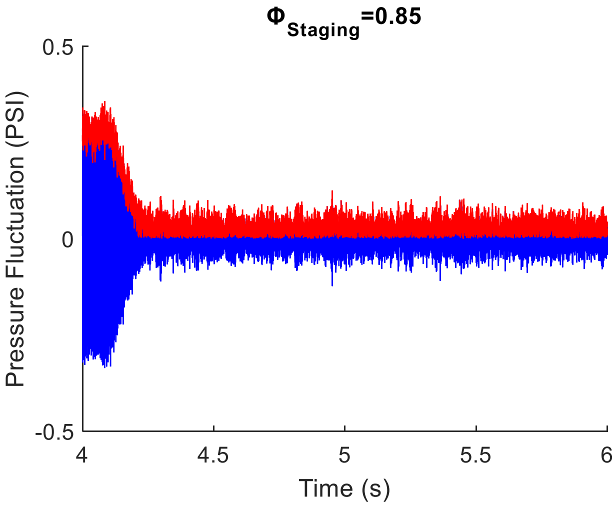
The growth/decay time of the instability reflects a natural time-scale of the system, and is dependent on staging level

<u>Center-nozzle: **ϕ=0.8**</u>

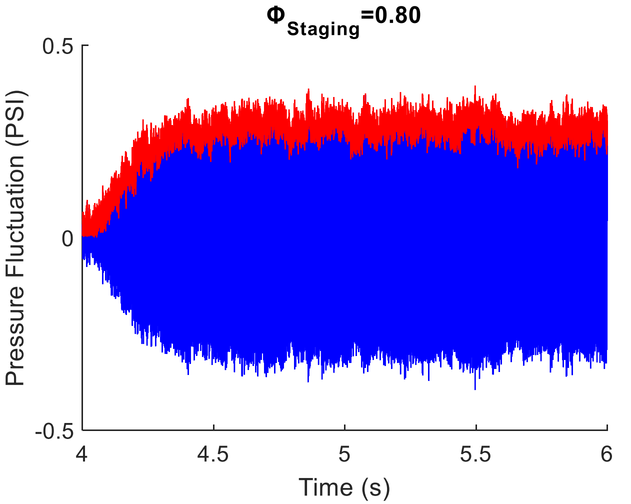
<u>Center-nozzle: **ϕ=0.85**</u>

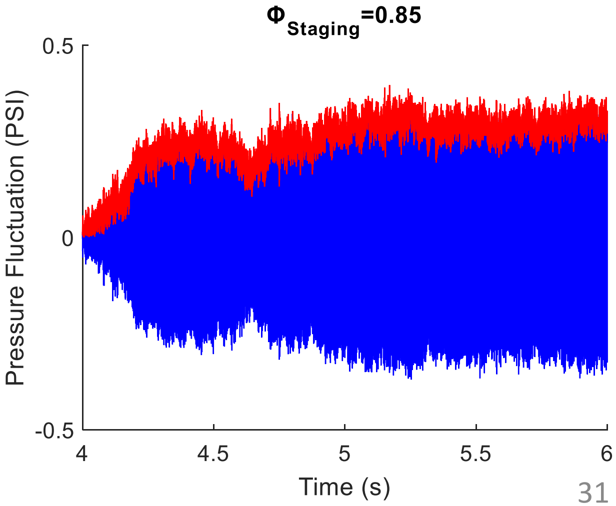
<u>Unstable → Stable</u>





<u>Stable → Unstable</u>





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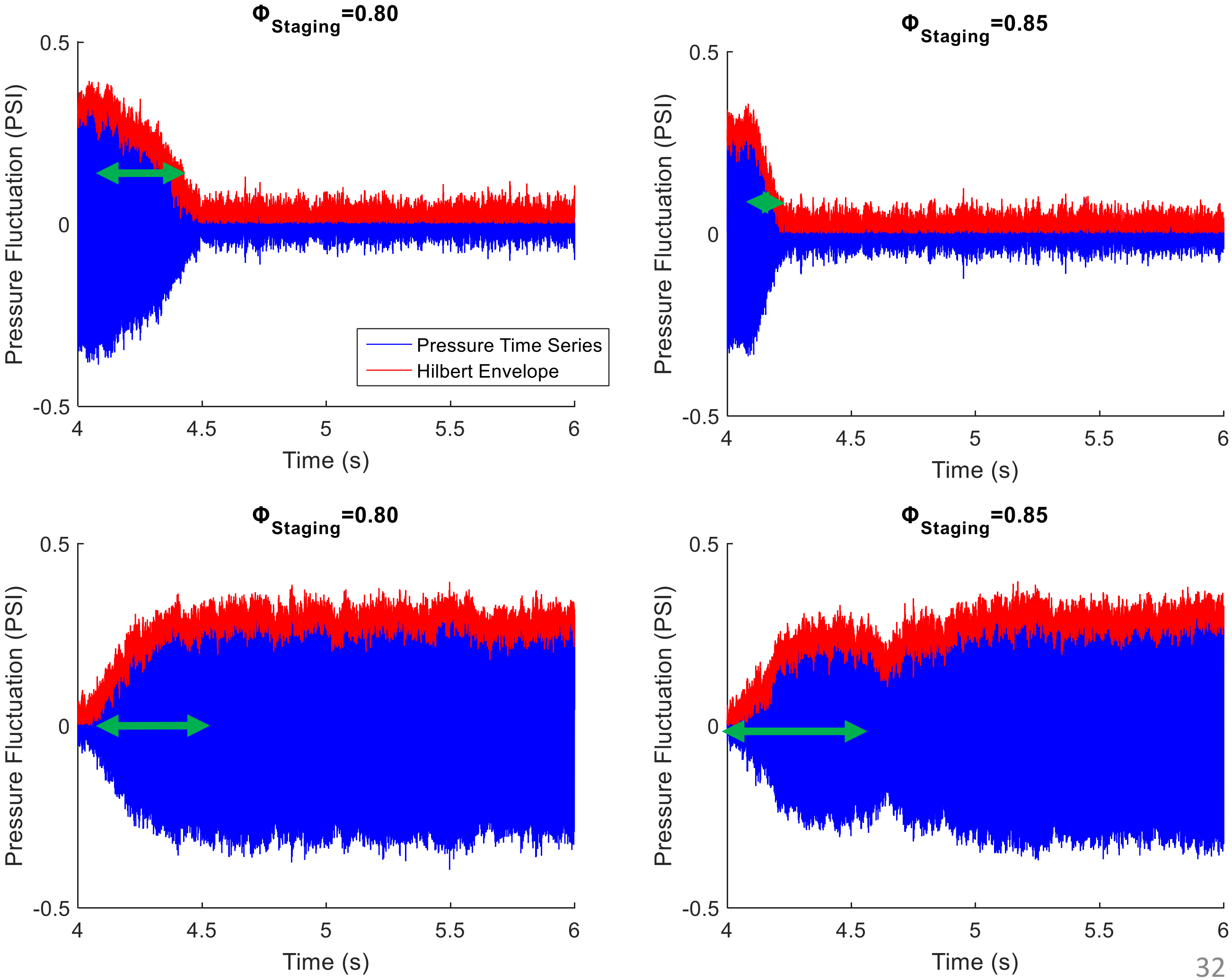
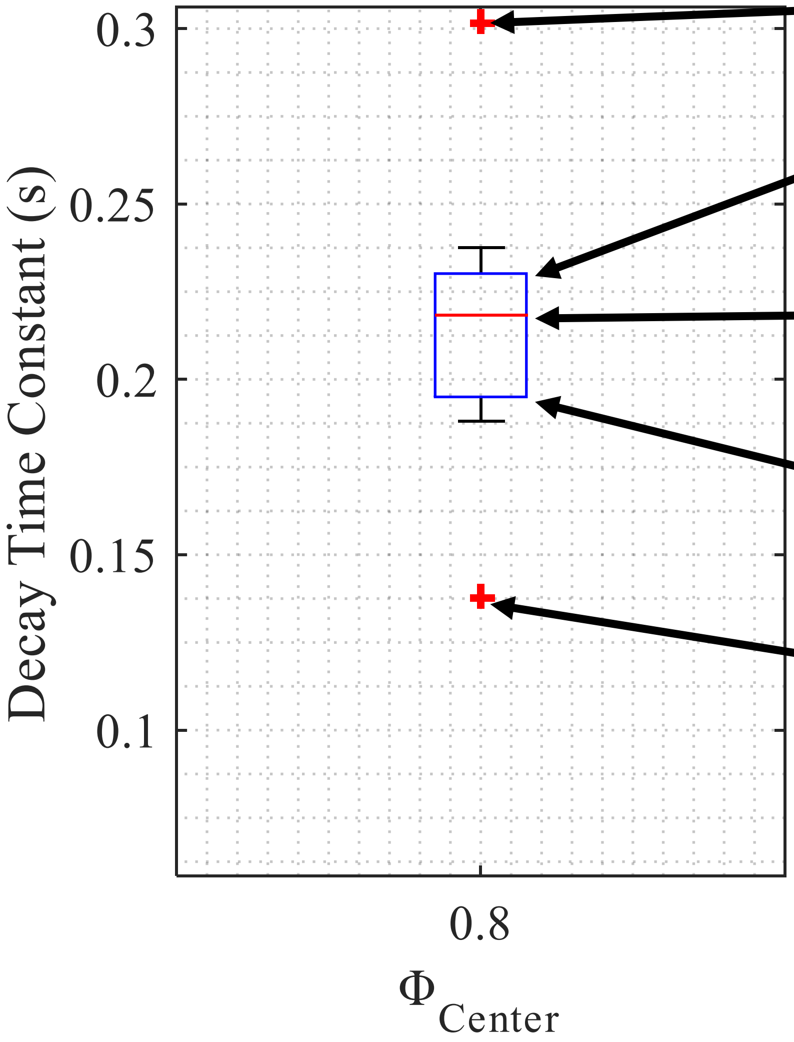
Center-nozzle: **ϕ=0.85**

Unstable → Stable

Stable → Unstable



Box-and-whisker plots provide a useful way to visualize ensemble data.



Maximum value

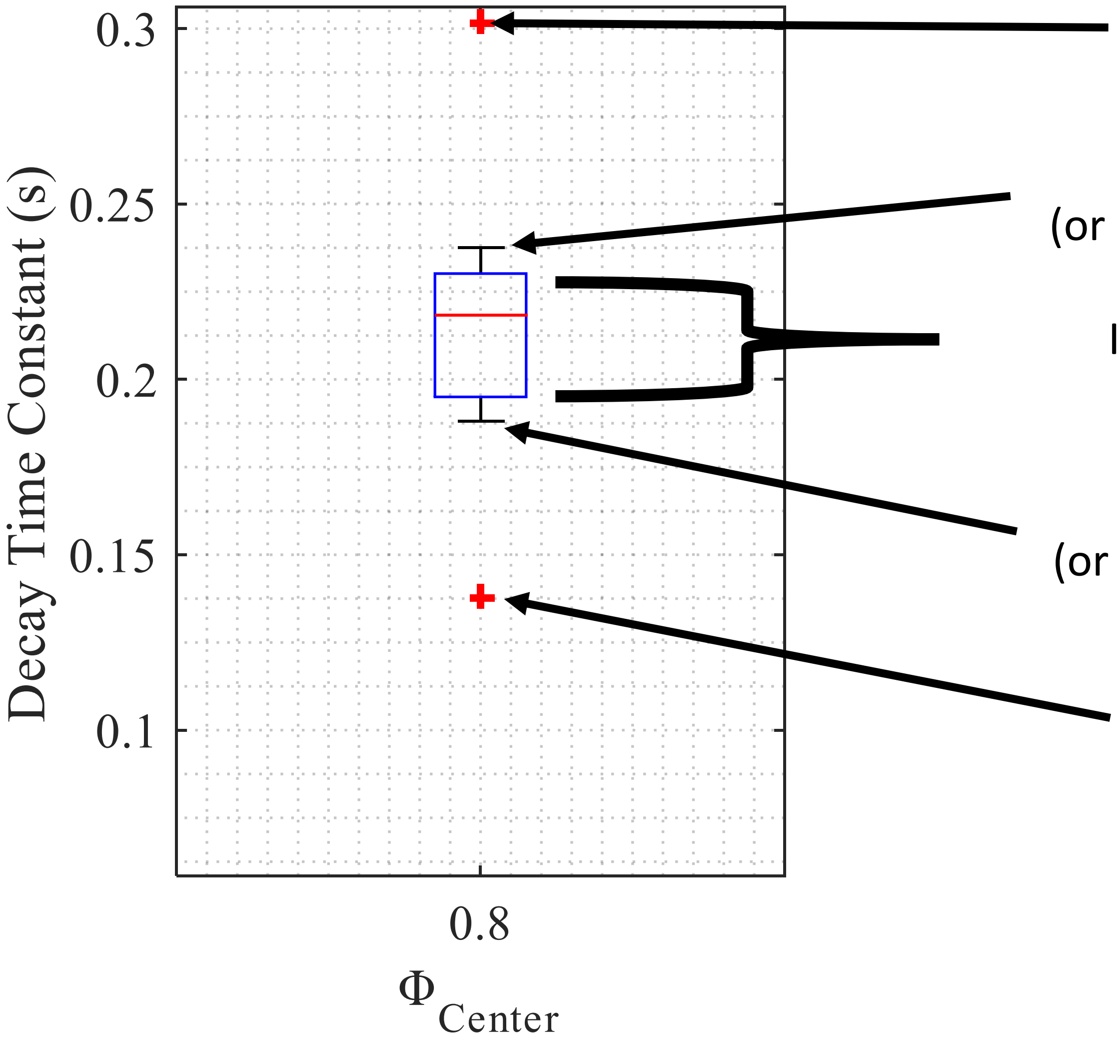
Median between maximum and median
of whole data set (third quartile)

Median (second quartile)

Median between minimum and median
of whole data set (first quartile)

Minimum value

Box-and-whisker plots provide a useful way to visualize ensemble data.



Maximum value (outlier)
>1.5 IQR from median

Median+1.5*IQR
(or maximum point if no outliers)

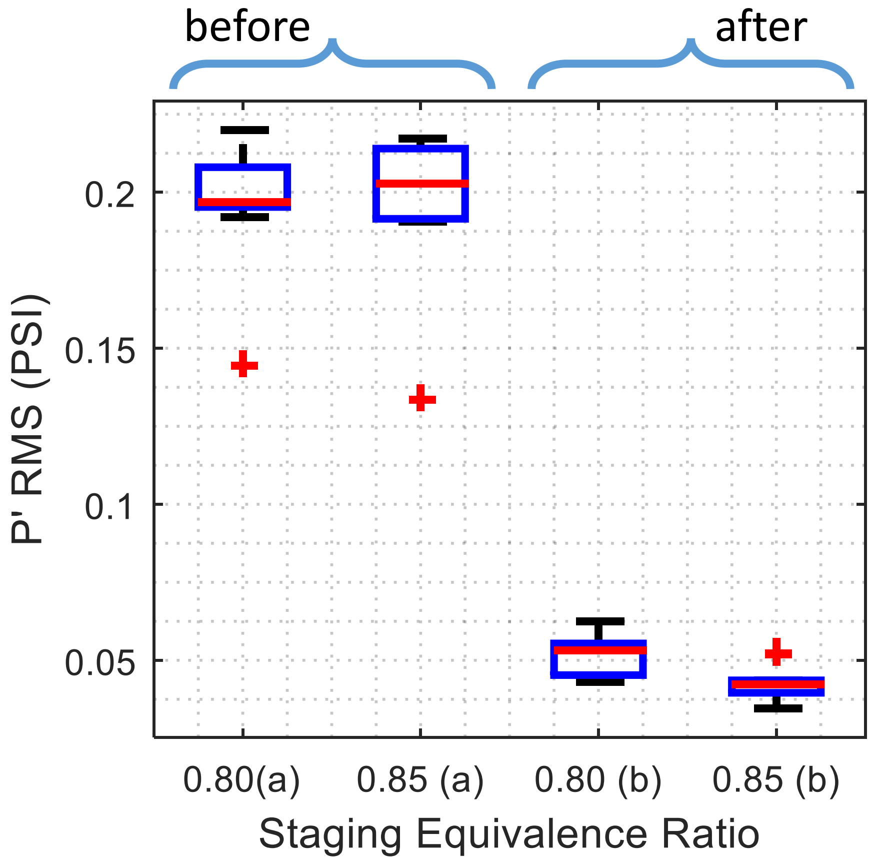
Inner Quartile Range (IQR)

Median-1.5*IQR
(or minimum point if no outliers)

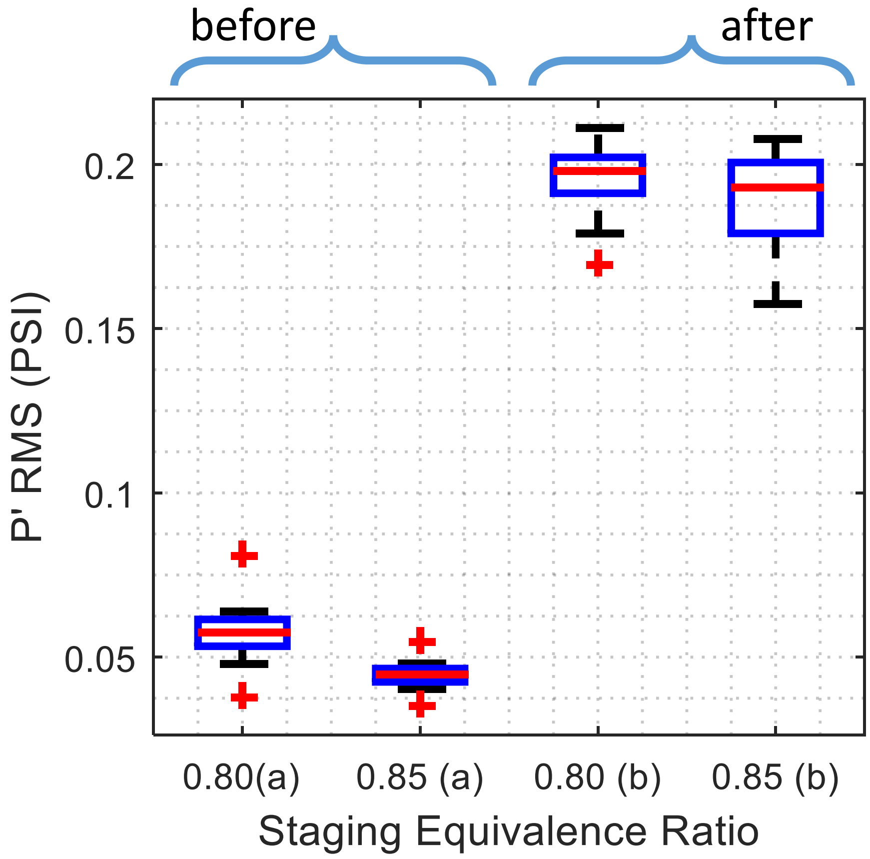
Minimum value (outlier)
<1.5 IQR from median

The pressures before and after the transient mirror the steady-state test results, showing high repeatability

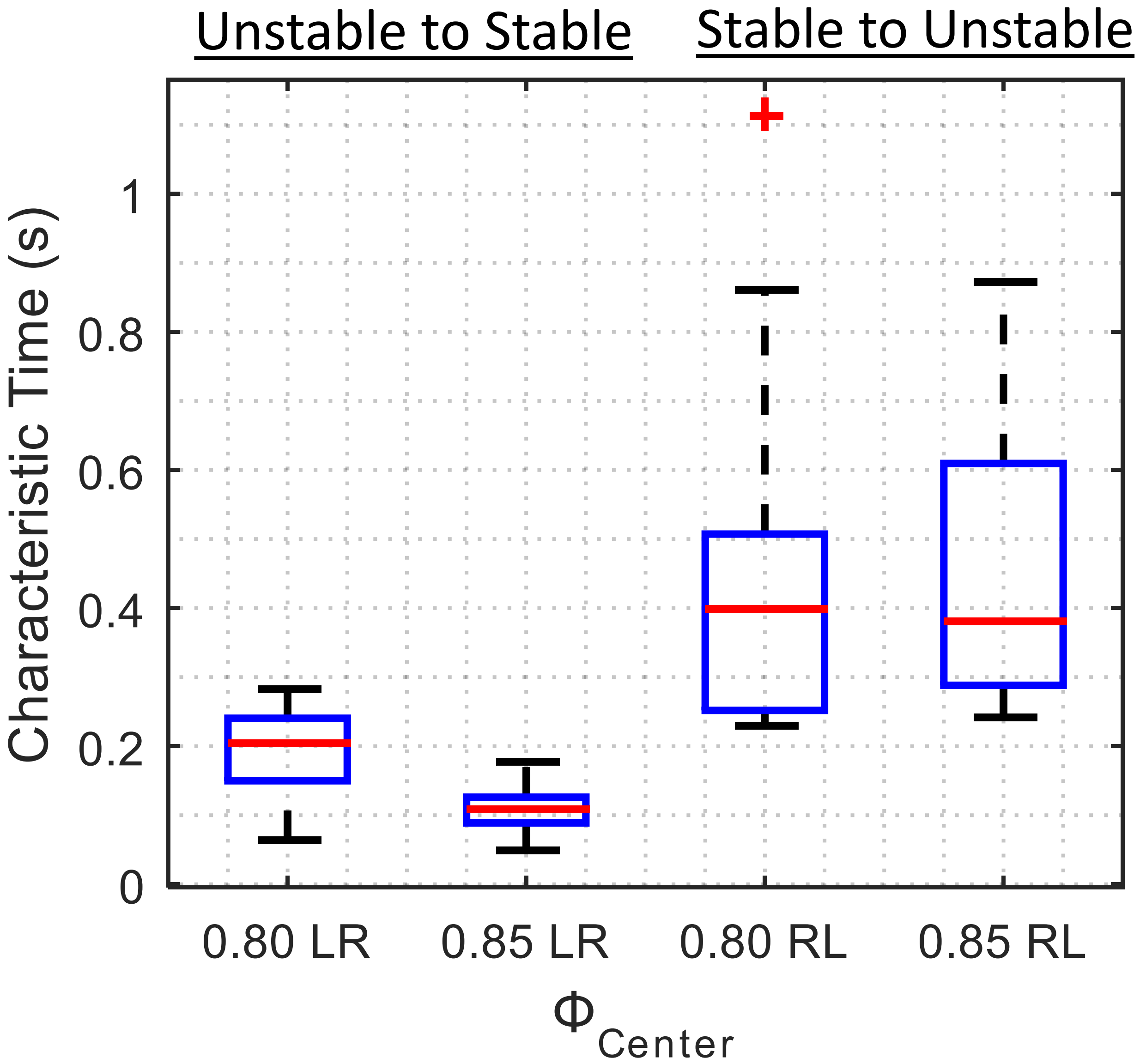
Unstable to Stable



Stable to Unstable

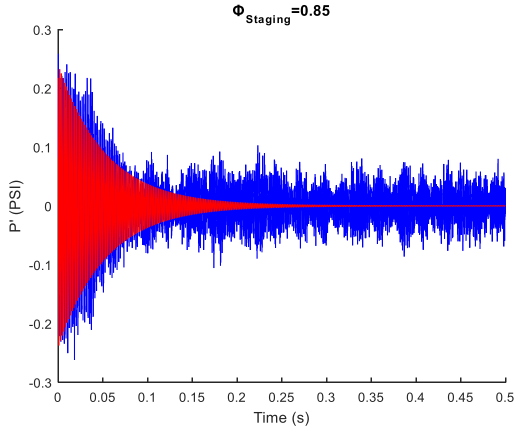


The characteristic decay time depends on staging amplitude, but the characteristic rise time does not appear to

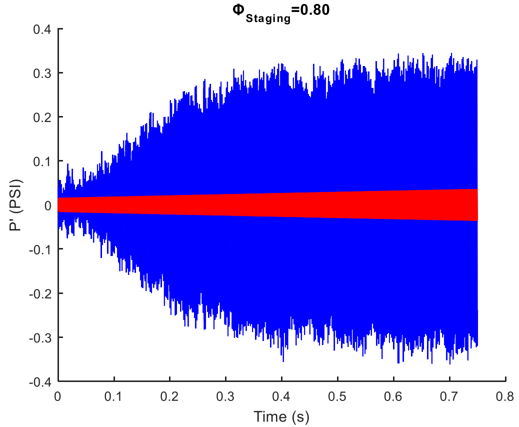


The functional form of the growth and decay profiles can help illuminate some of the physics involved in the processes

Model 1: Damped linear oscillator decaying at a single frequency



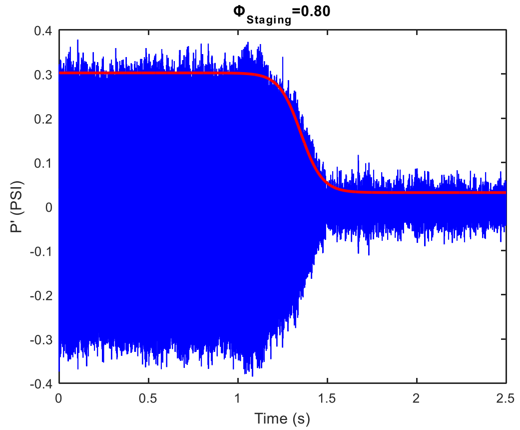
$$P'(t) = Ae^{-\lambda t} + AB * \left(1 - e^{-\lambda t}\right) * \sin(\omega t + \Phi)$$

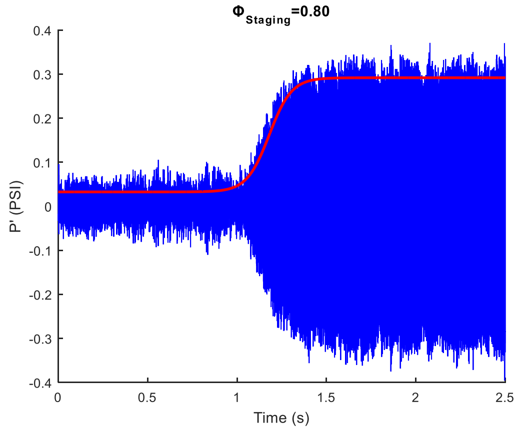


$$P'(t) = ABe^{-\lambda t} + B * \left(1 - e^{-\lambda t}\right) * \sin(\omega t + \Phi)$$

Model 2: General Logistic Growth/Decay

$$P'(t) = \frac{A - B}{\left(1 + e^{k(t - t_0)}\right)} + B$$





Overview of presentation

- Project motivation and approach

- Year 1 Results:
  - Steady-state fuel staging – mechanisms for instability suppression
  - Transient fuel staging – natural system timescales

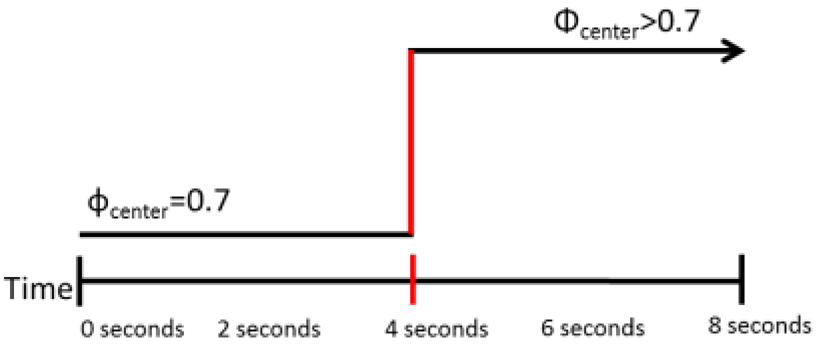
- Conclusions and next steps

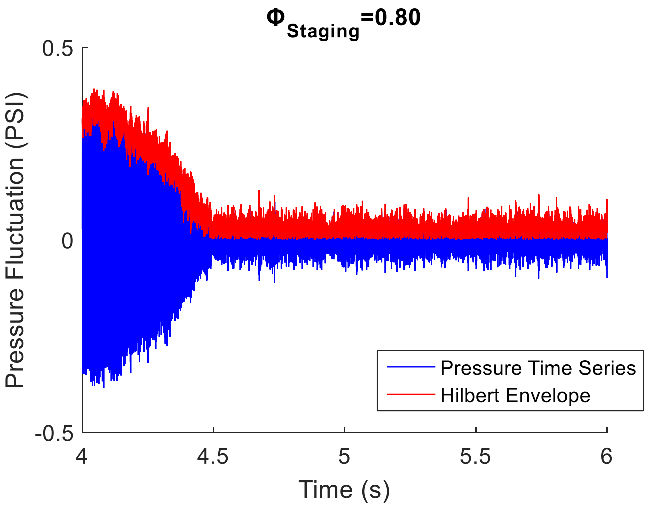
Wrap-up and Questions

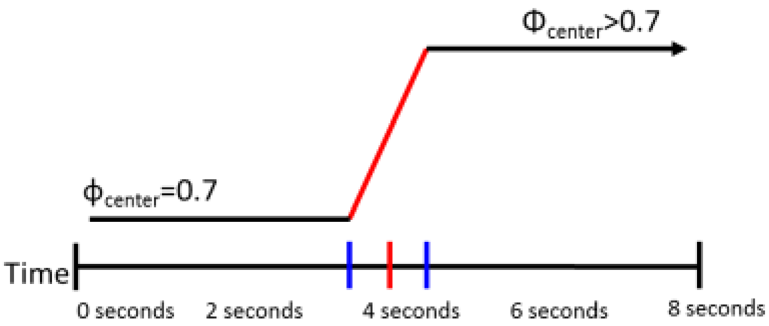
- **Key findings to date**
  - Combustion instability can be suppressed using fuel staging in experimental facility, as it is in operational gas turbines
  - Recent data may provide mechanism by which fuel staging suppresses instability; can be used as baseline for transient tests
  - Transient instability growth and decay rates are different, likely driven by different processes in the combustor

- **Next steps**
  - Develop better models for capturing instability growth and decay processes → likely non-linear oscillators
  - Transient testing at different fuel-staging time-scales
  - Comparisons to single-nozzle operation

Different fuel-staging time-scales will be used to quantify the sensitivity of the combustor stability to transient timescale







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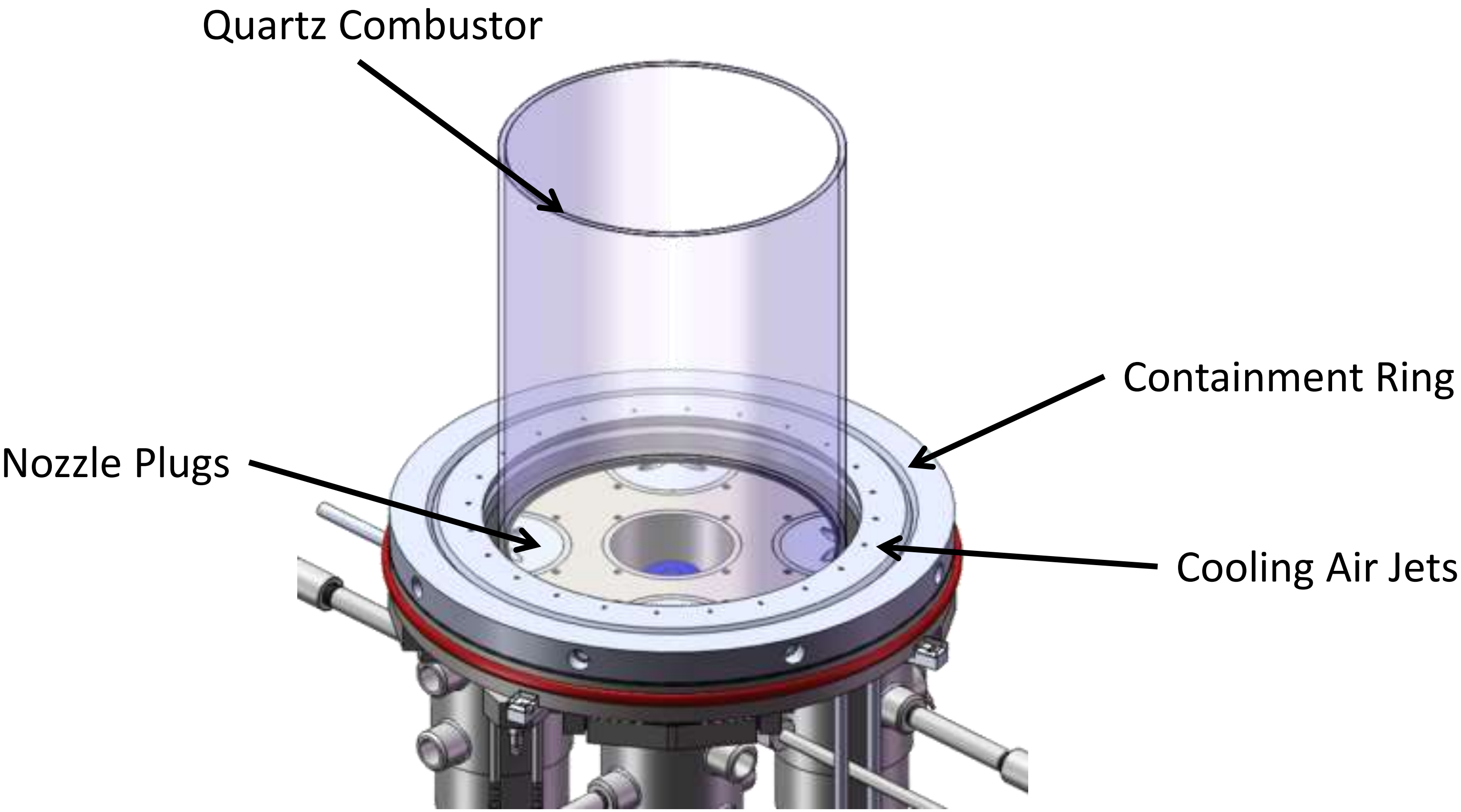
Single-nozzle operation will be completed on the same rig with the same nozzles for direct comparison to current data



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Questions?

Understanding Transient Combustion Phenomena in Low-NO_x Gas Turbines

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