Understanding Transient Combustion Phenomena in Low-NO_x Gas Turbines

Project DE-FE0025495, Oct. 2015 – Sept. 2018
Program Monitor: Mark Freeman

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Co-PI: Dom Santavicca, Ph.D.
RE: Stephen Peluso, Ph.D.
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Undergraduates: Olivia Sekulich, Jackson Lee

Industry Partner: GE Global Research
Keith McManus, Tony Dean, Fei Han

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PennState

Overview of presentation

- Project motivation and approach

- Year 2 Results:
  - Impact of staging timescale on instability transitions
  - Impact of non-axisymmetric staging
  - Comparisons of single- and multi-nozzle combustors

- Conclusions and next steps

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

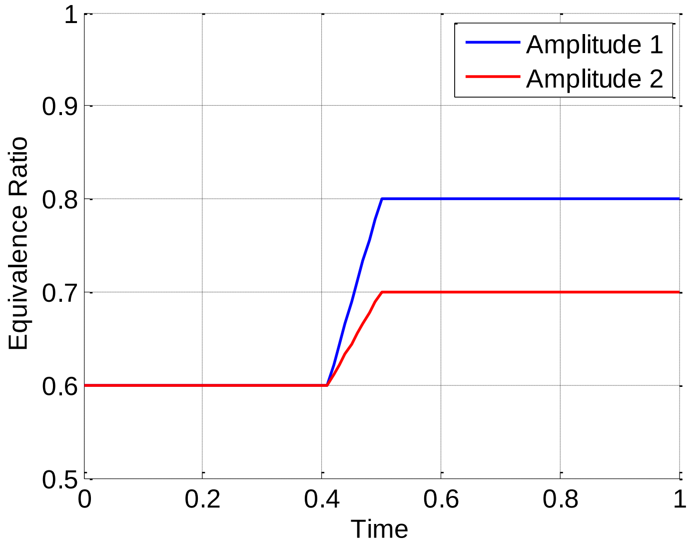
— Two major deliverables for the program:

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

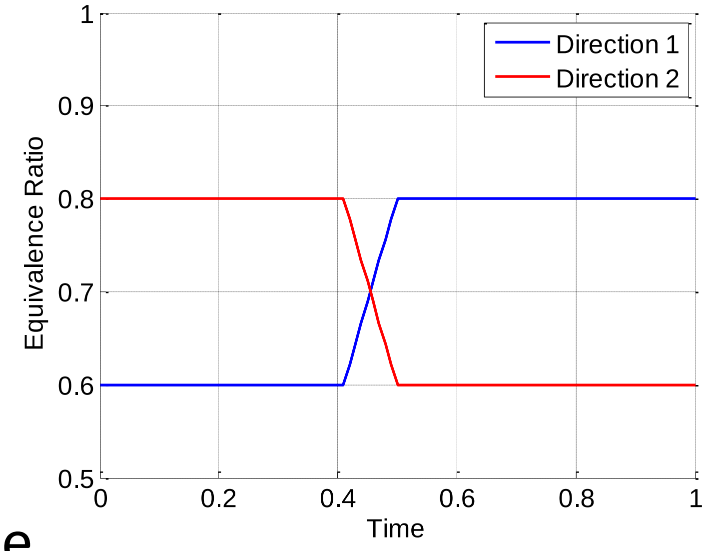
2. Development of a stability prediction or quantification framework

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

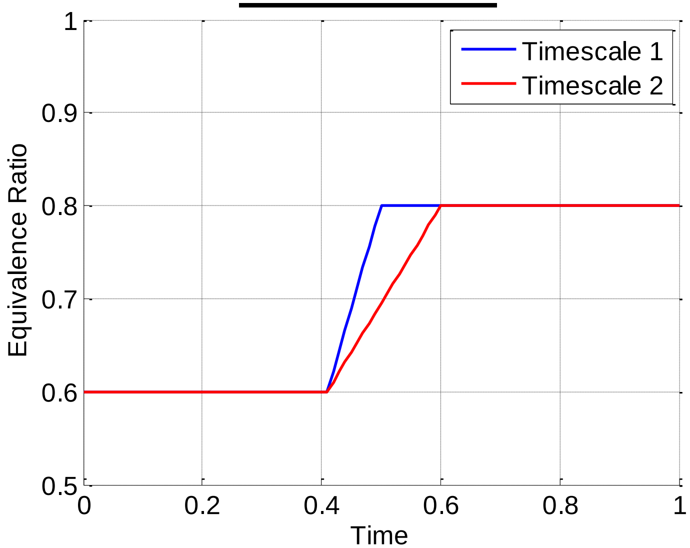
Amplitude



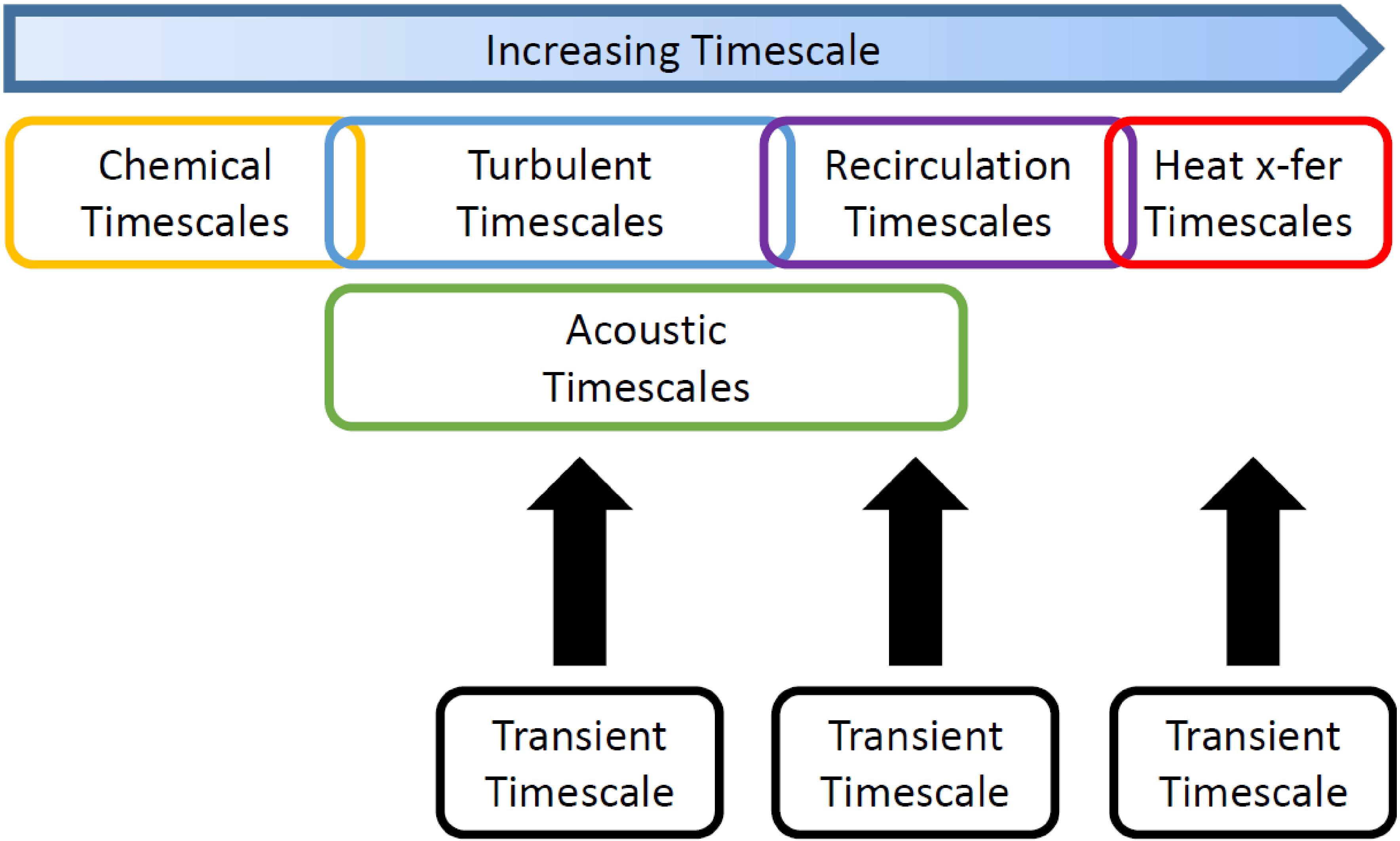
Direction



Timescale



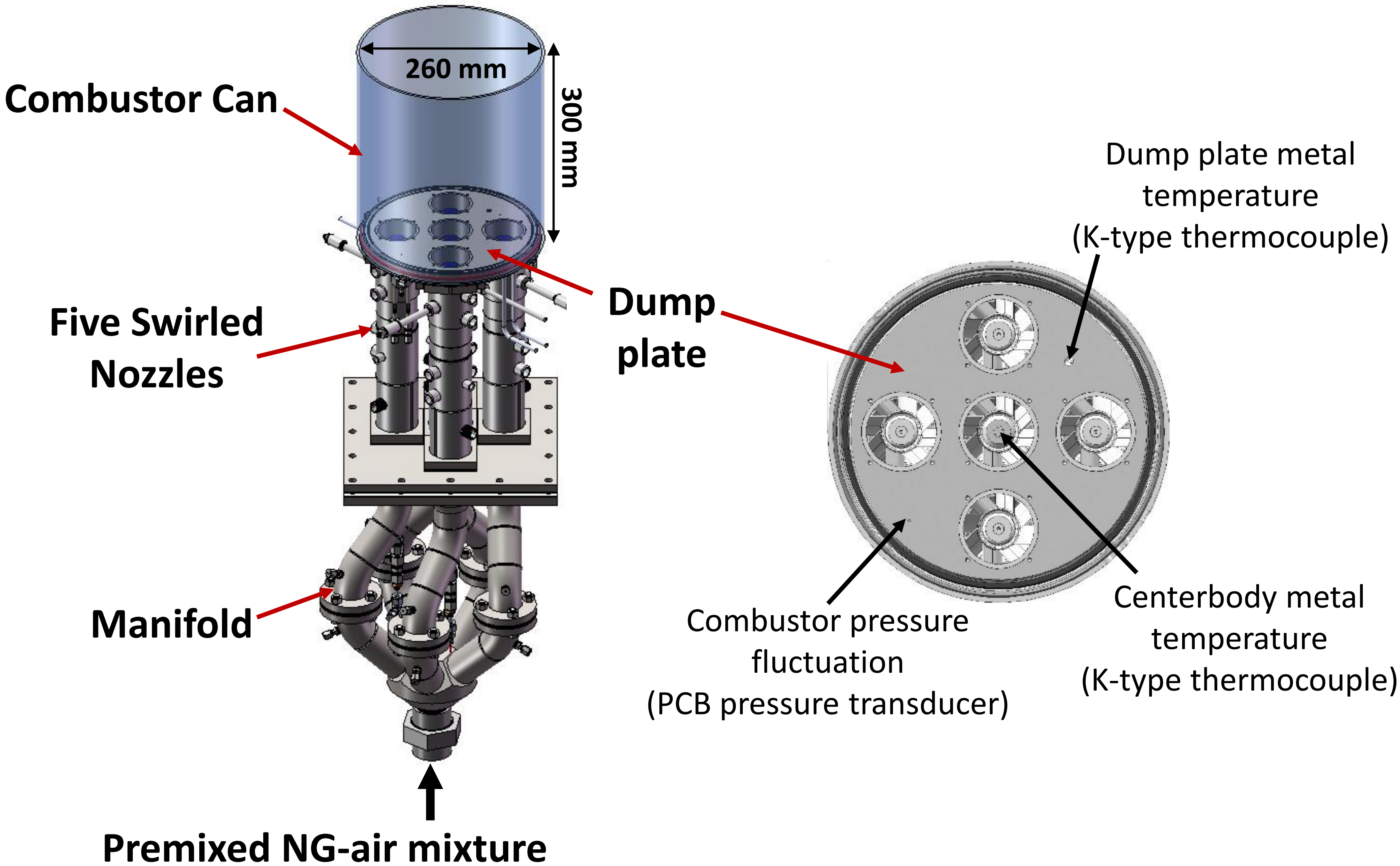
Varying the transient timescales allows for different processes to equilibrate during the transient, changing the path



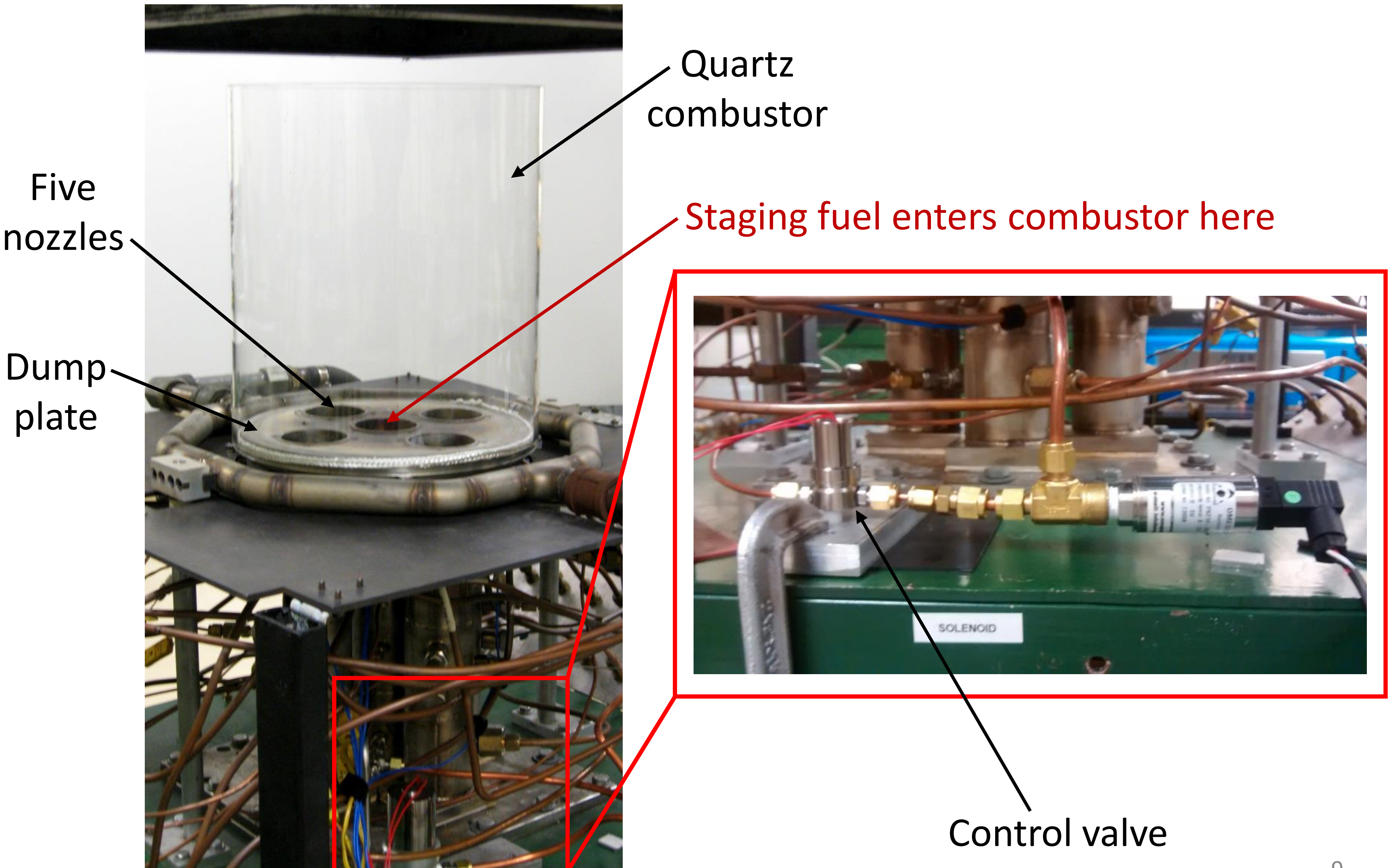
Project Management Plan – progress to date

- **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

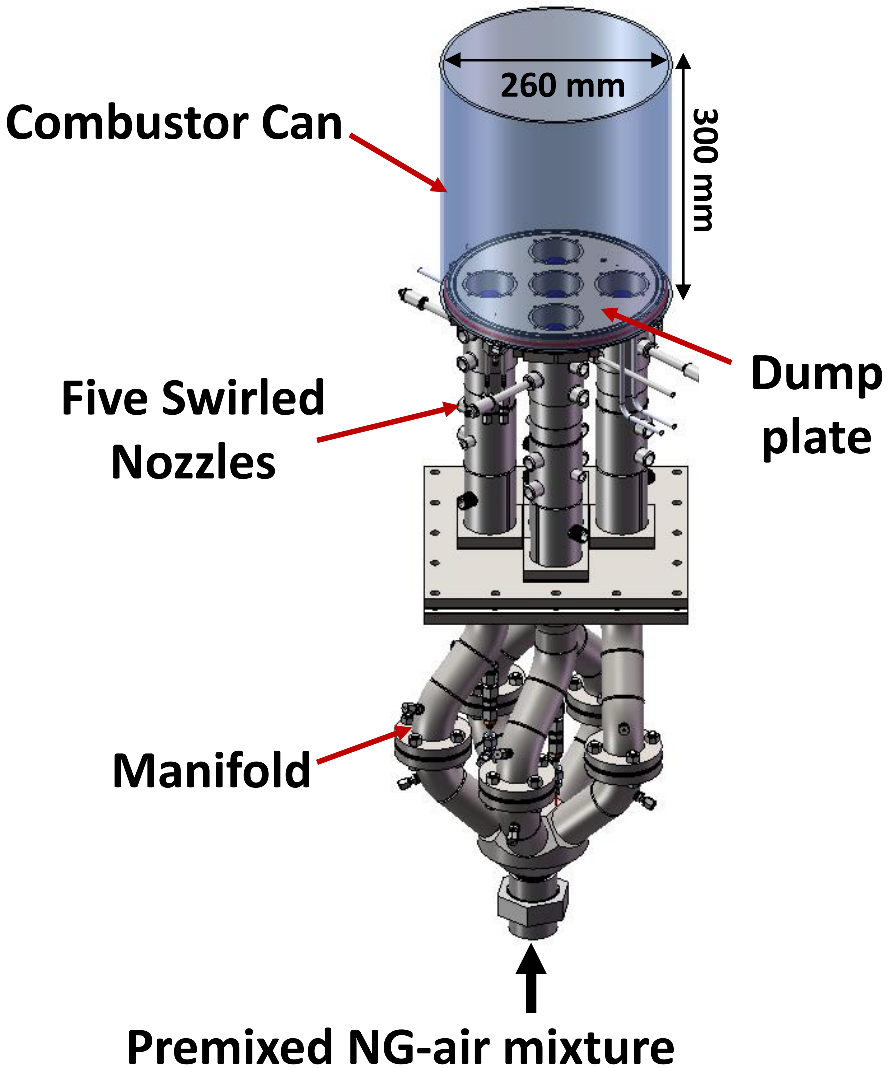
Experimental facilities include both a single-nozzle and multi-nozzle combustor, fuel splitting on multi-nozzle only

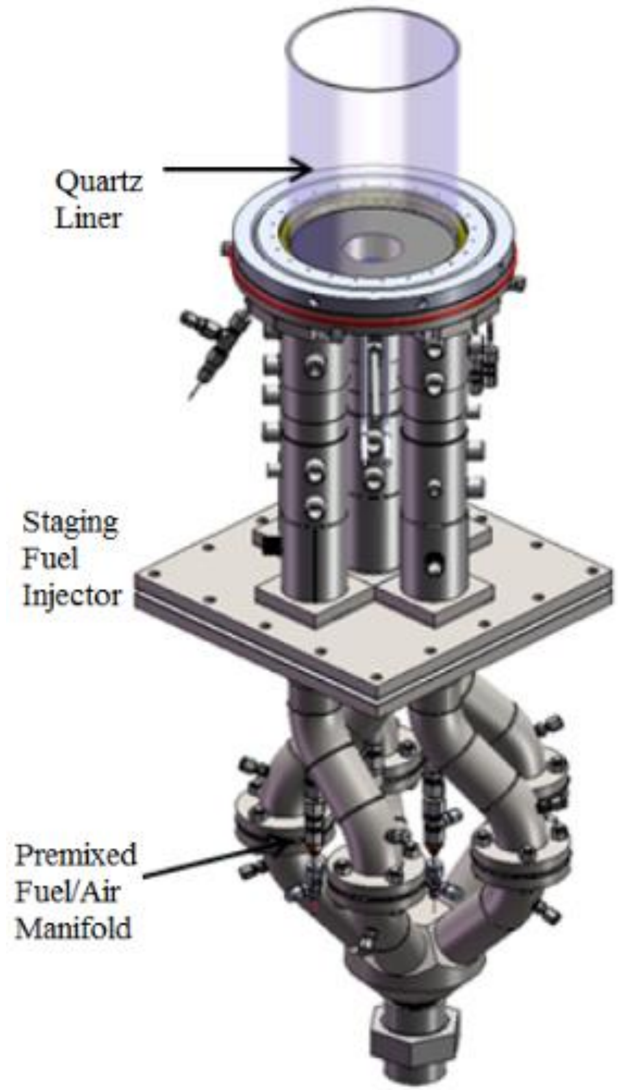


TASK 2: Hardware modification focused on a valve with linear actuation to control fuel flow transients for fuel-splitting studies



Single-nozzle combustor is created by plugging four nozzles and using a smaller quartz liner with the same dump ratio





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  - Impact of non-axisymmetric staging
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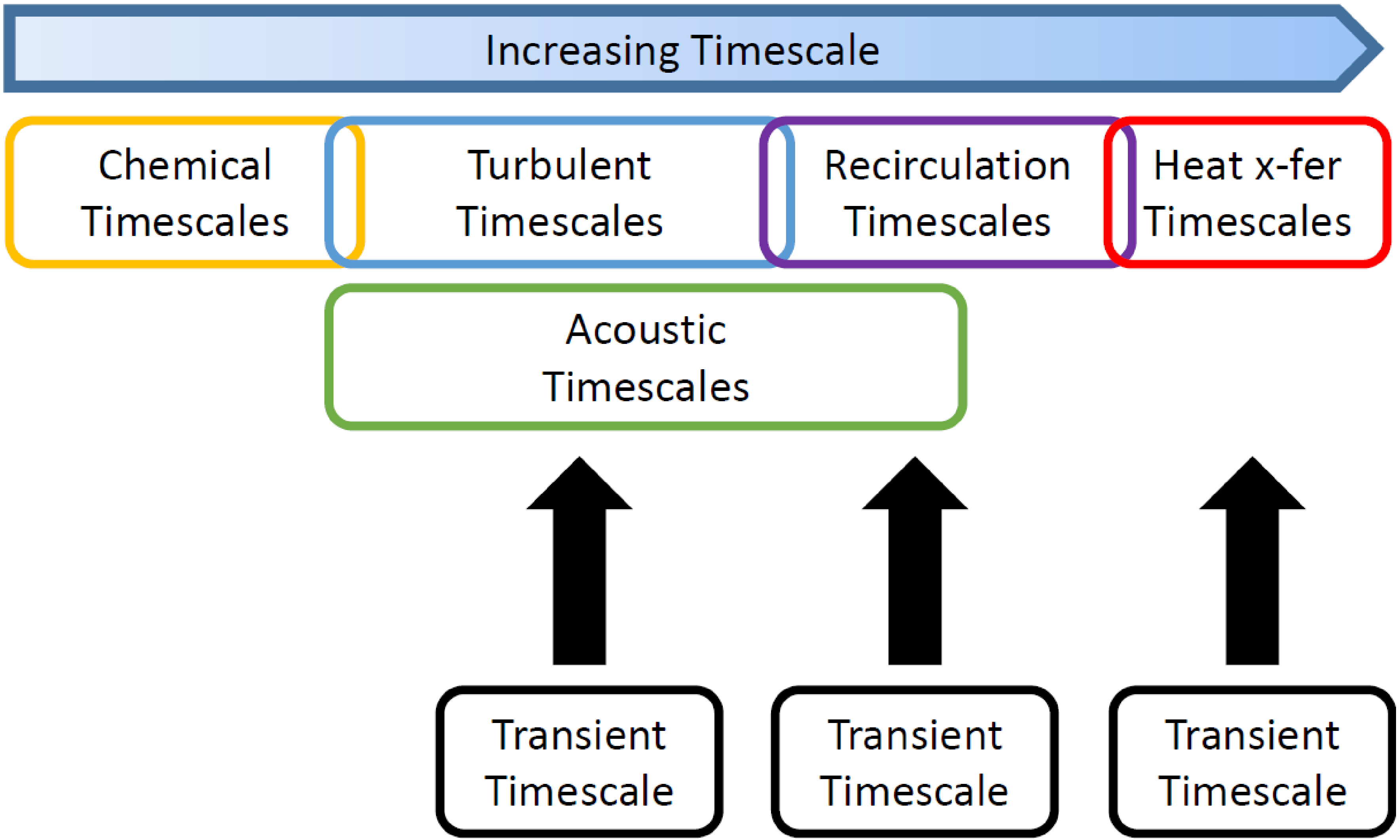
Publications to date explore the impact of transient amplitude and direction on flame behavior

— Samarasinghe, J., Culler, W., Quay, B., Santavicca, D., O'Connor, J. (2017) "The Effect of Fuel Staging on the Structure and Instability Characteristics of Swirl-Stabilized Flames in a Lean Premixed Multinozzle Can Combustor," *Journal of Engineering for Gas Turbines and Power*, **139**(12), p. 121504

— Culler, W., Samarasinghe, J., Quay, B., Santavicca, D., O'Connor, J., (2017) "The Effect of Transient Fuel Staging on Self-Excited Instabilities in a Multi-Nozzle Model Gas Turbine Combustor," *ASME Turbo Expo*, Charlotte, NC, GT2017-63479

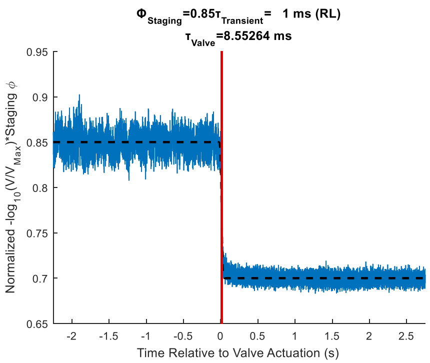
The goal of this task is to understand what changes about the transient as we execute it at different timescales



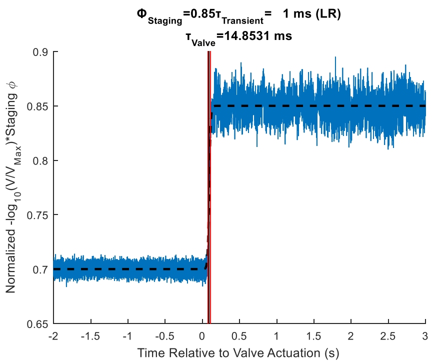
Of the cases we've tested, we've identified "short" vs. "long" timescales that group based on transient behavior

Short Timescales

Valve Close

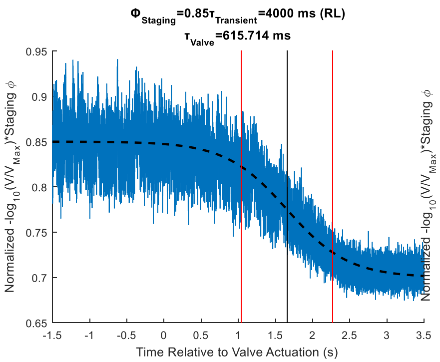


Valve Open

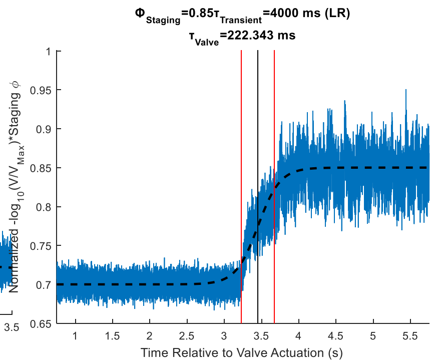


Long Timescales

Valve Close



Valve Open



Of the cases we've tested, we've identified "short" vs. "long" timescales that group based on transient behavior

Short Timescales

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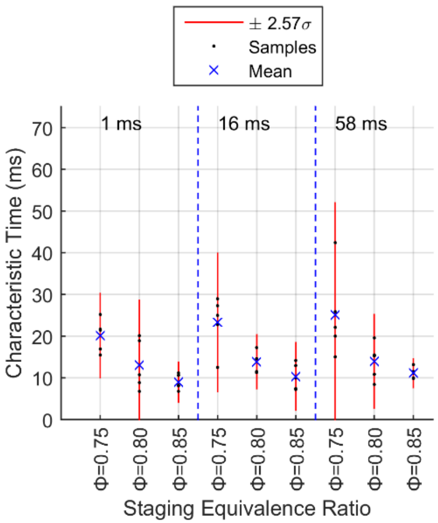
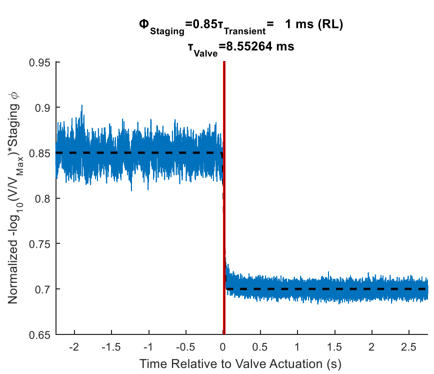
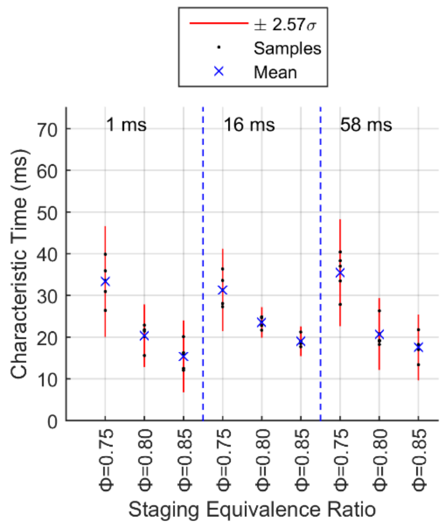
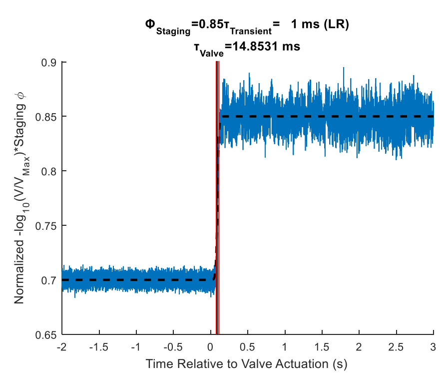




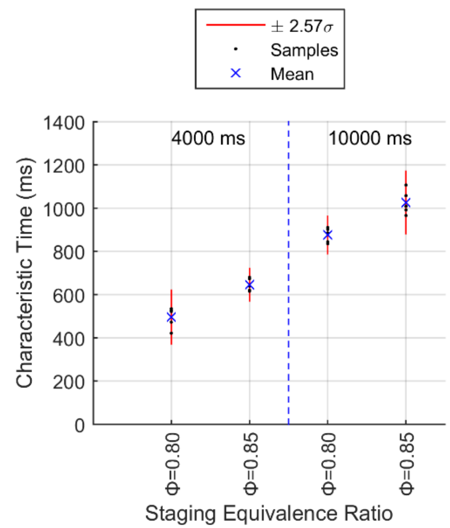
Valve Open

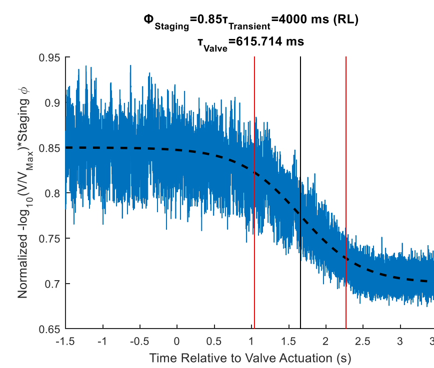




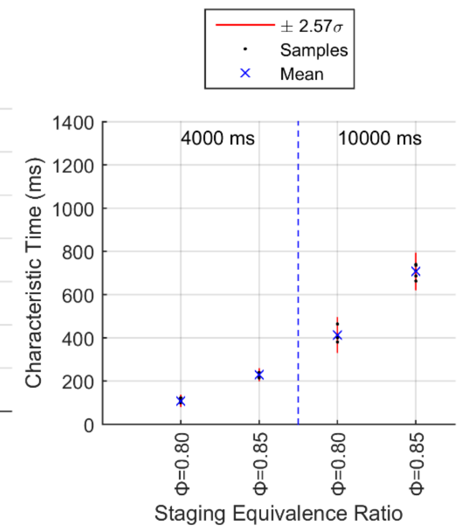
Long Timescales

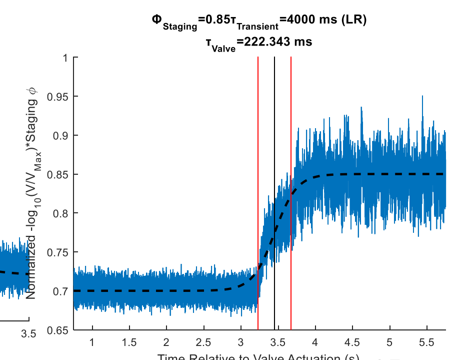
Valve Close





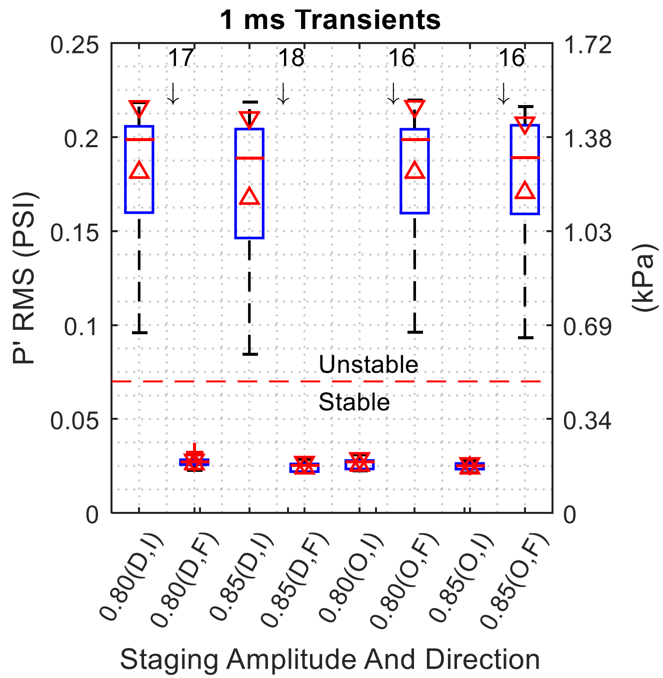
Valve Open

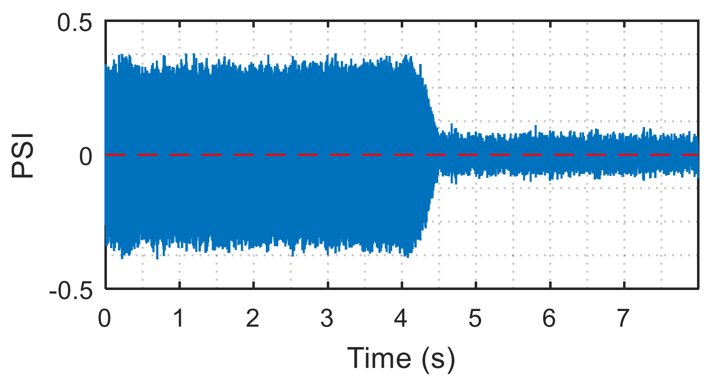




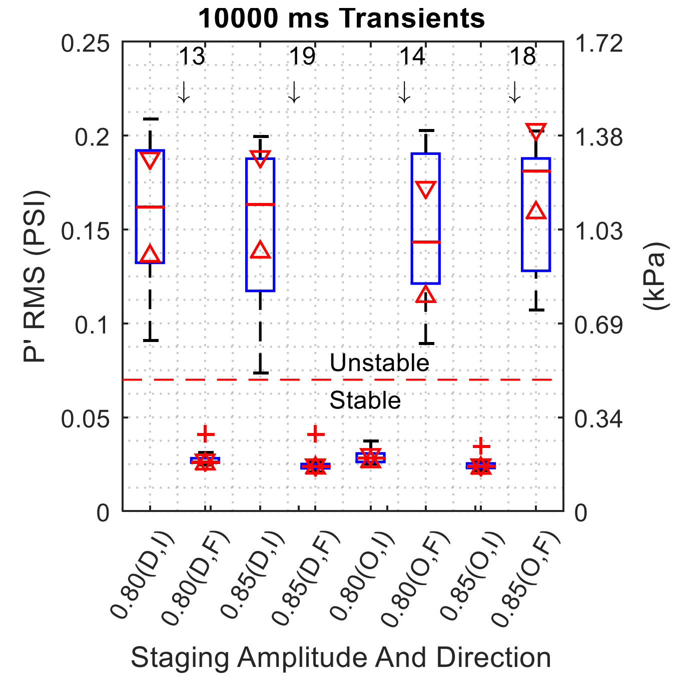
The end state of the transient is not dependent on timescale, only staging level of the center nozzle

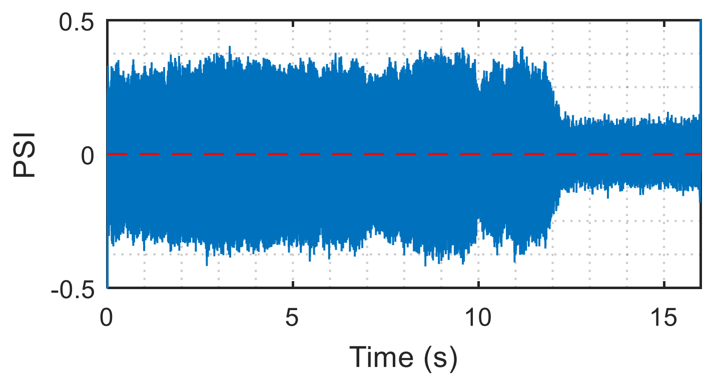
Short Timescales





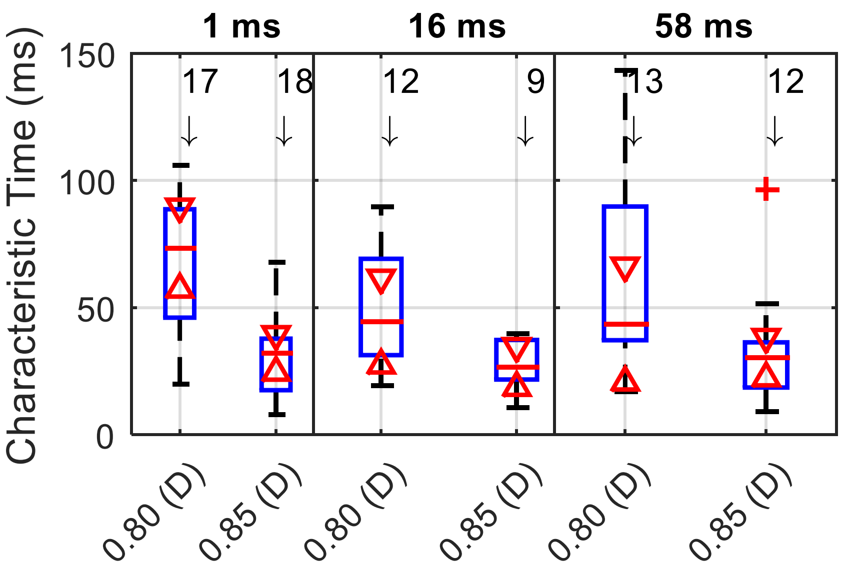
Long Timescales

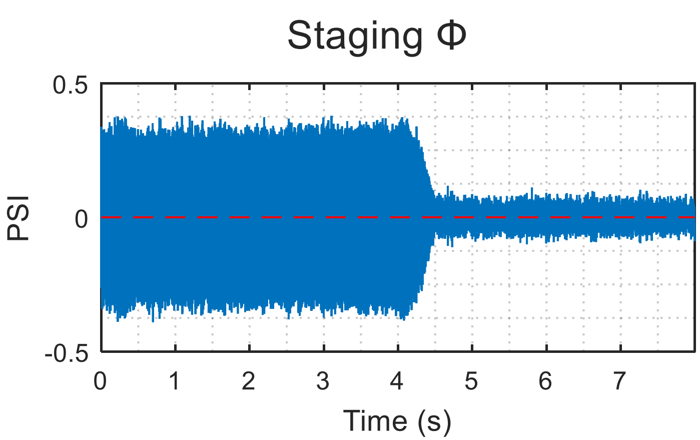




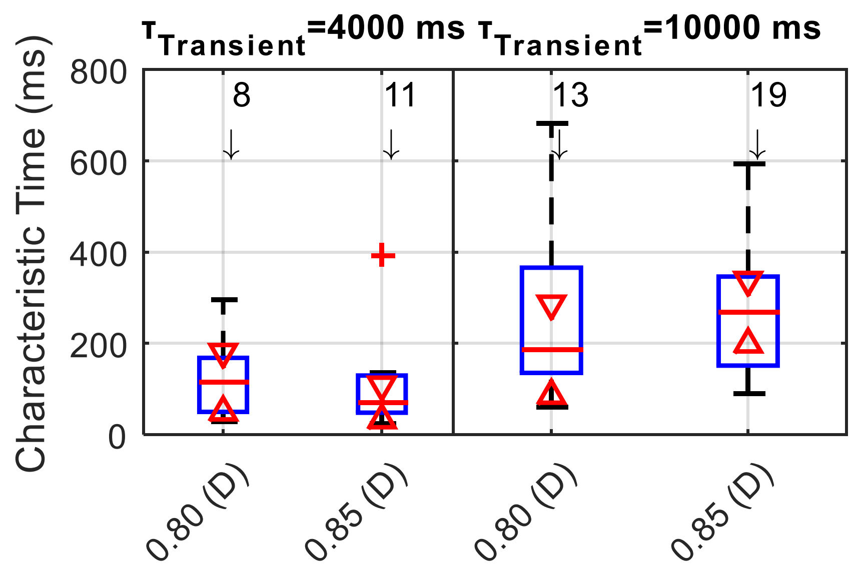
The instability transition times differ for different transition timescales, showing key timescale dependency

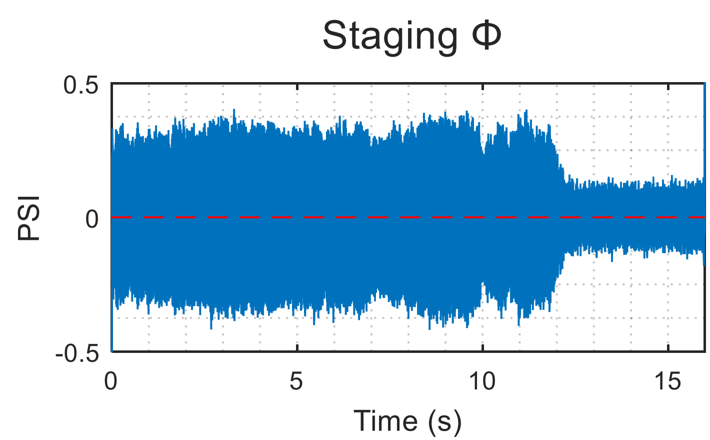
Short Timescales





Long Timescales





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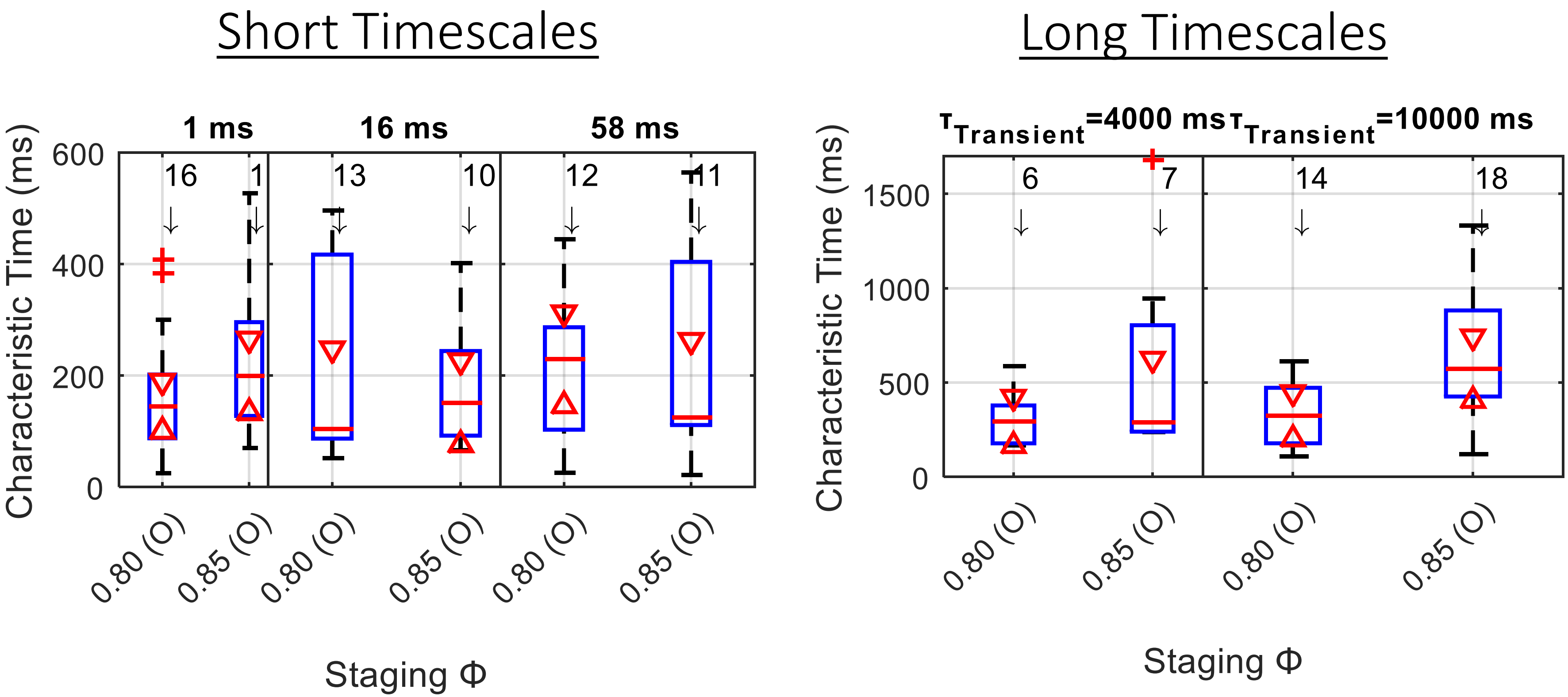
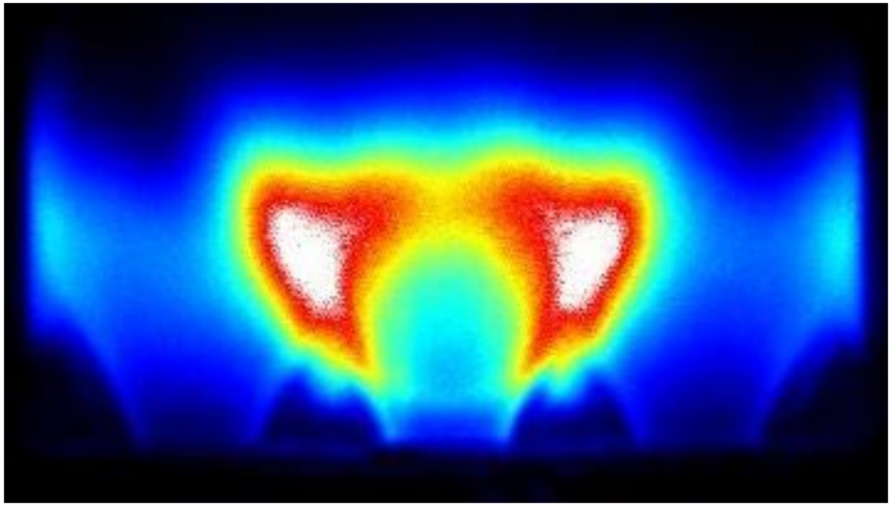


CH* chemiluminescence images are used to characterize flame structure, fluctuation, and phase

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

Line-of-sight photograph of multi-nozzle flame



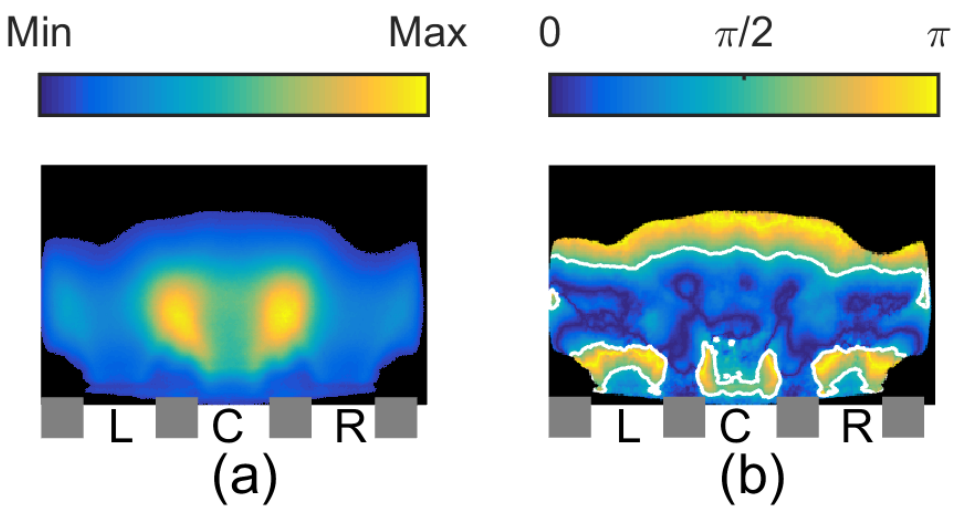
Line-of-sight CH* chemiluminescence image of multi-nozzle flame

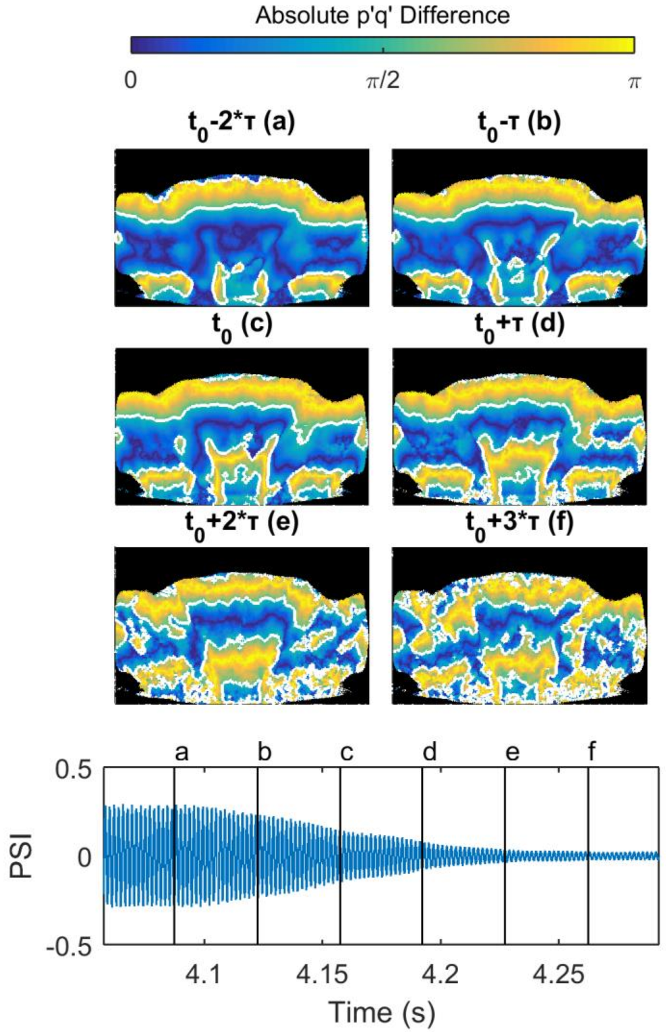
Pseudo color map is applied to chemiluminescence images

Low Intensity  **High Intensity**

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

Instantaneous phase analysis is helping to identify the mechanisms at play during the transient





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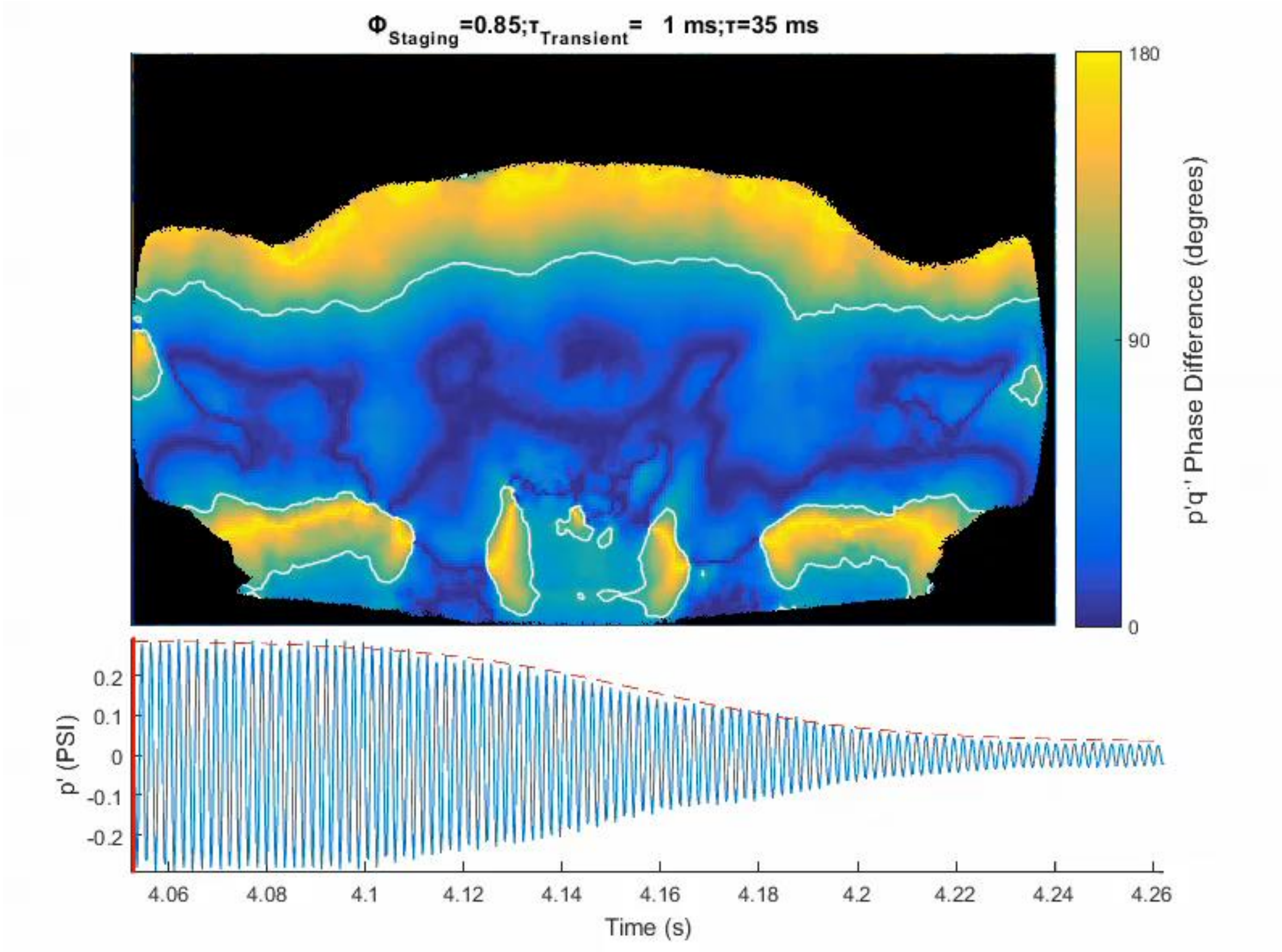

Paper in preparation for Combustion and Flame

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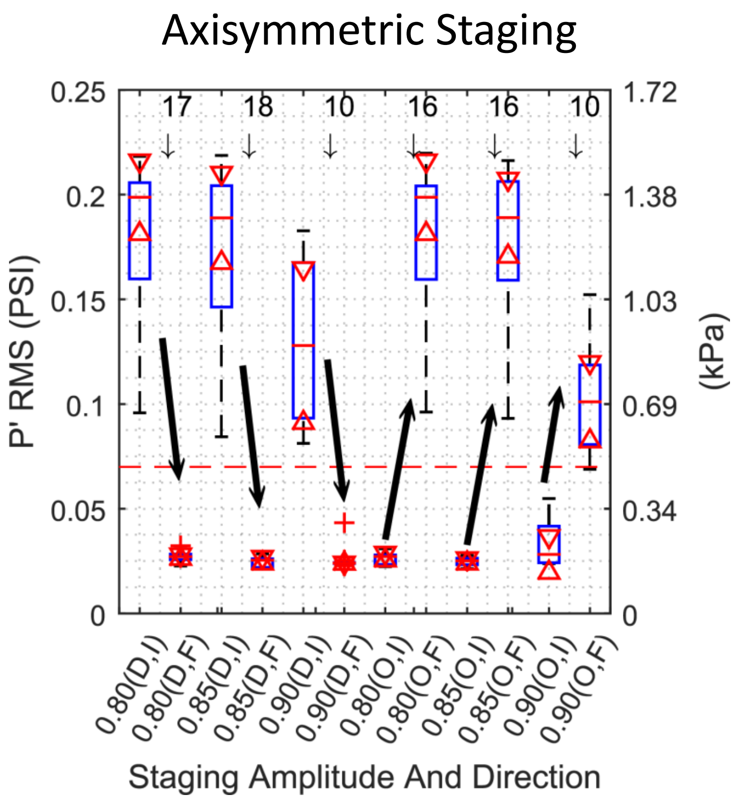
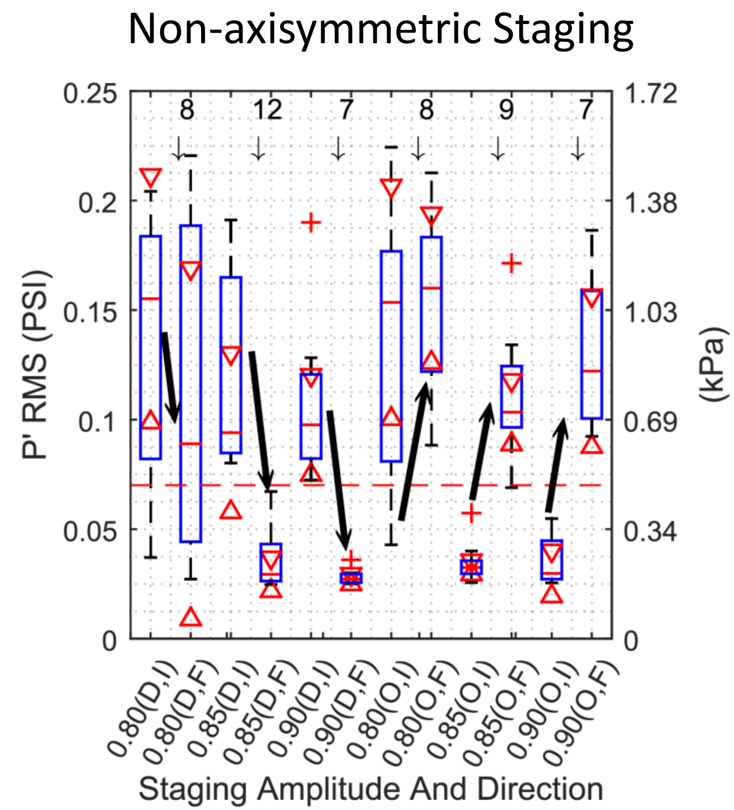
  - Impact of non-axisymmetric staging
    - *With credit to Dr. Bobby Noble, EPRI*
  - Comparisons of single- and multi-nozzle combustors
- Conclusions and next steps

We have found that non-axisymmetric staging is less effective than axisymmetric staging, a likely result of flame interaction





Work submitted to ASME Turbo Expo:

Culler, W., Chen, X., Peluso, S., Santavicca, D., O'Connor, J., Noble, D. (2018) "Comparison of center nozzle staging to outer nozzle staging in a multi-flame combustor," ASME Turbo Expo, Lillestrom, Norway

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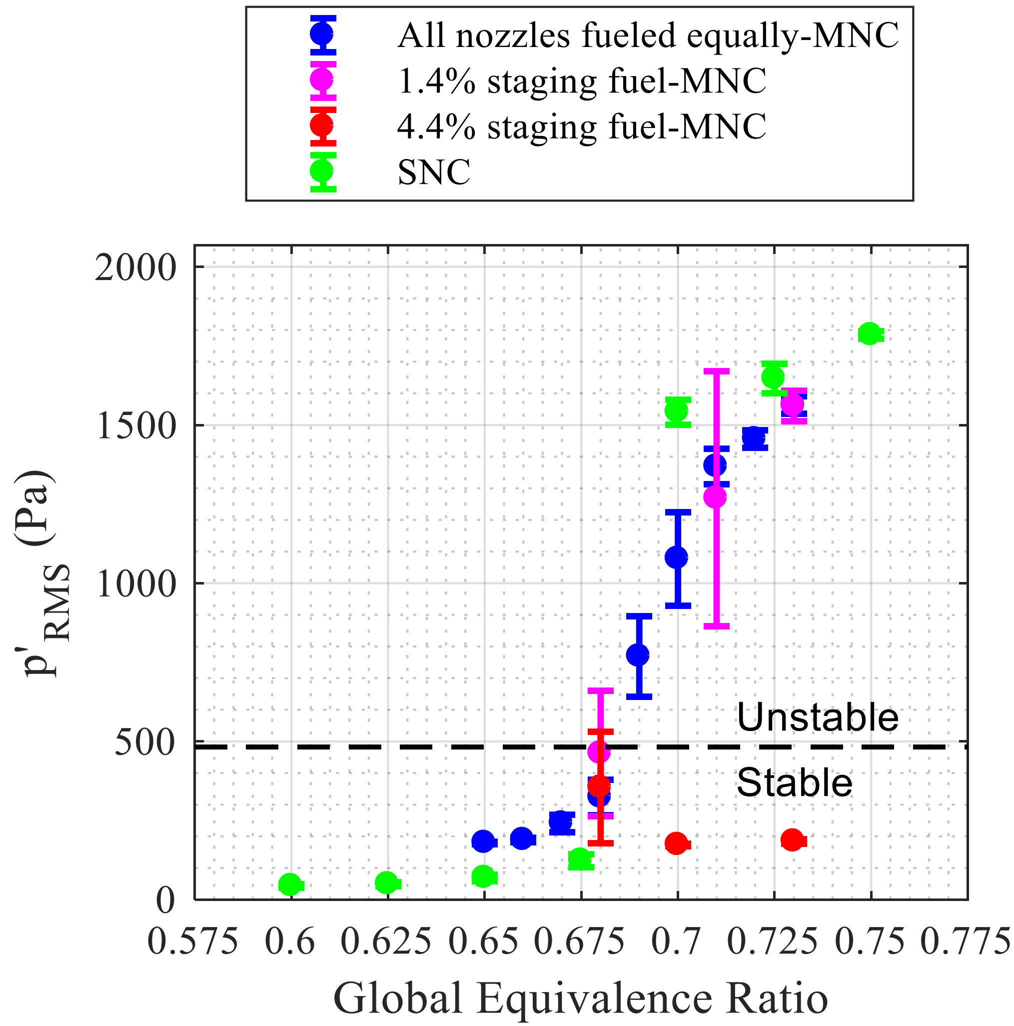
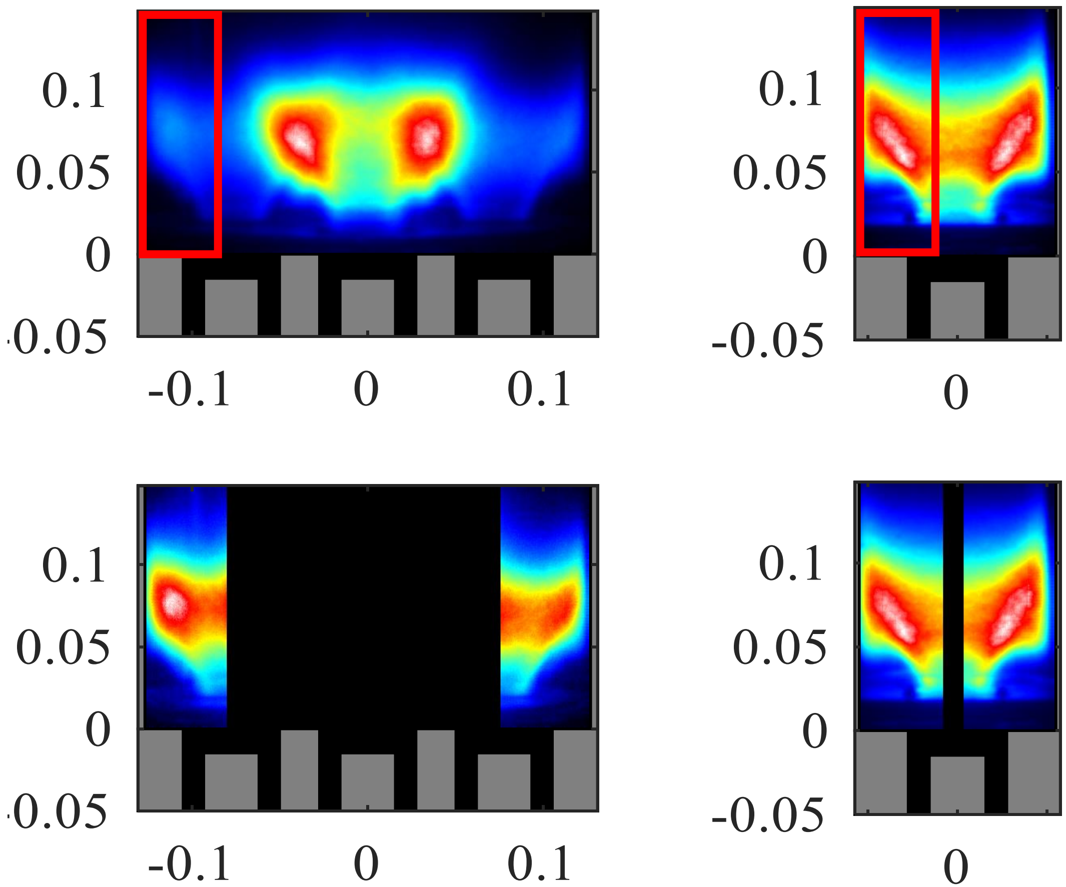
We've chosen a condition where the transition equivalence ratio is the same for the single-, multi-nozzle rigs



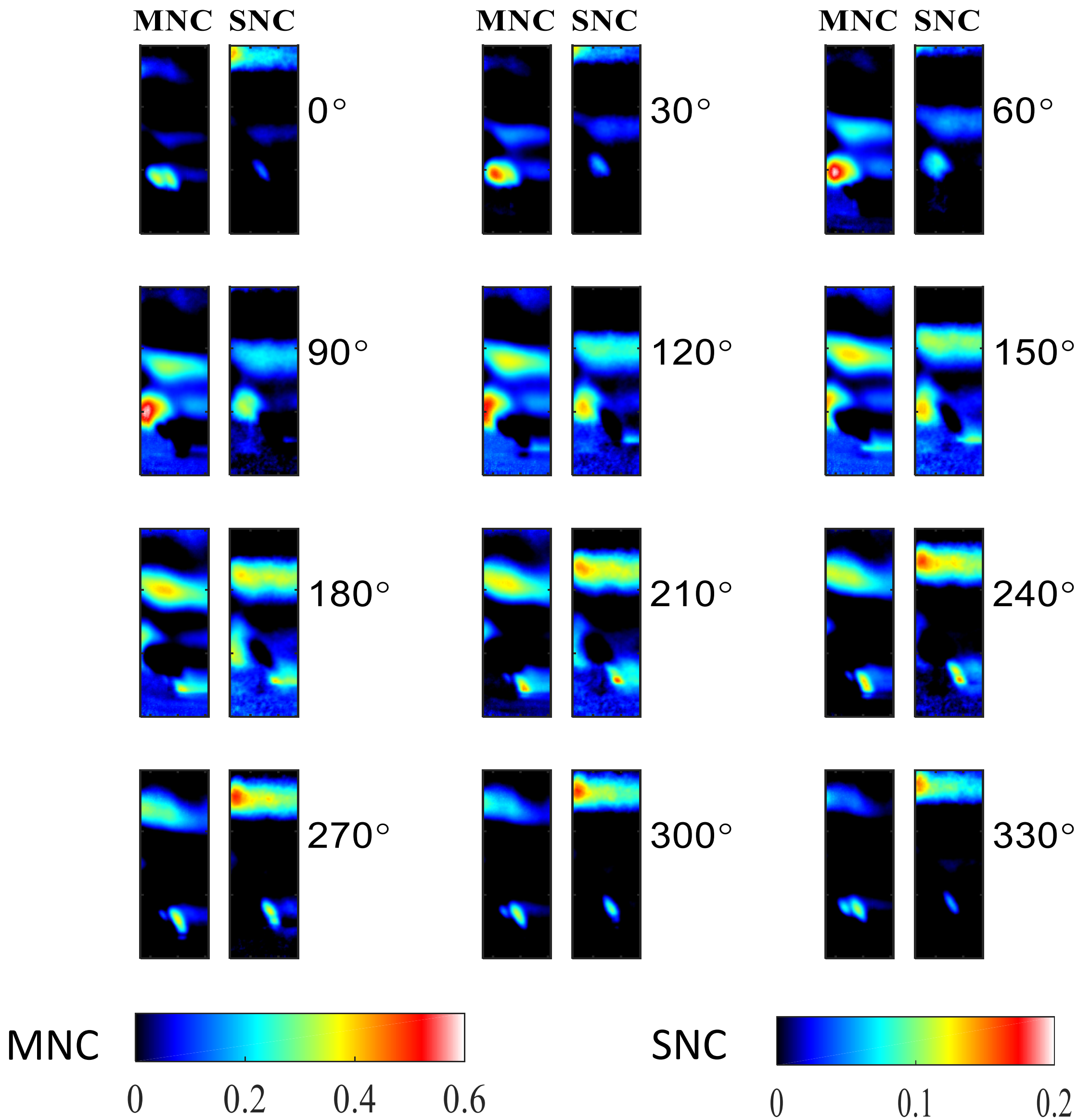
In order to compare flame dynamics, we consider the outer-half of the outer flame in the multi-nozzle vs. single-nozzle

Full image:

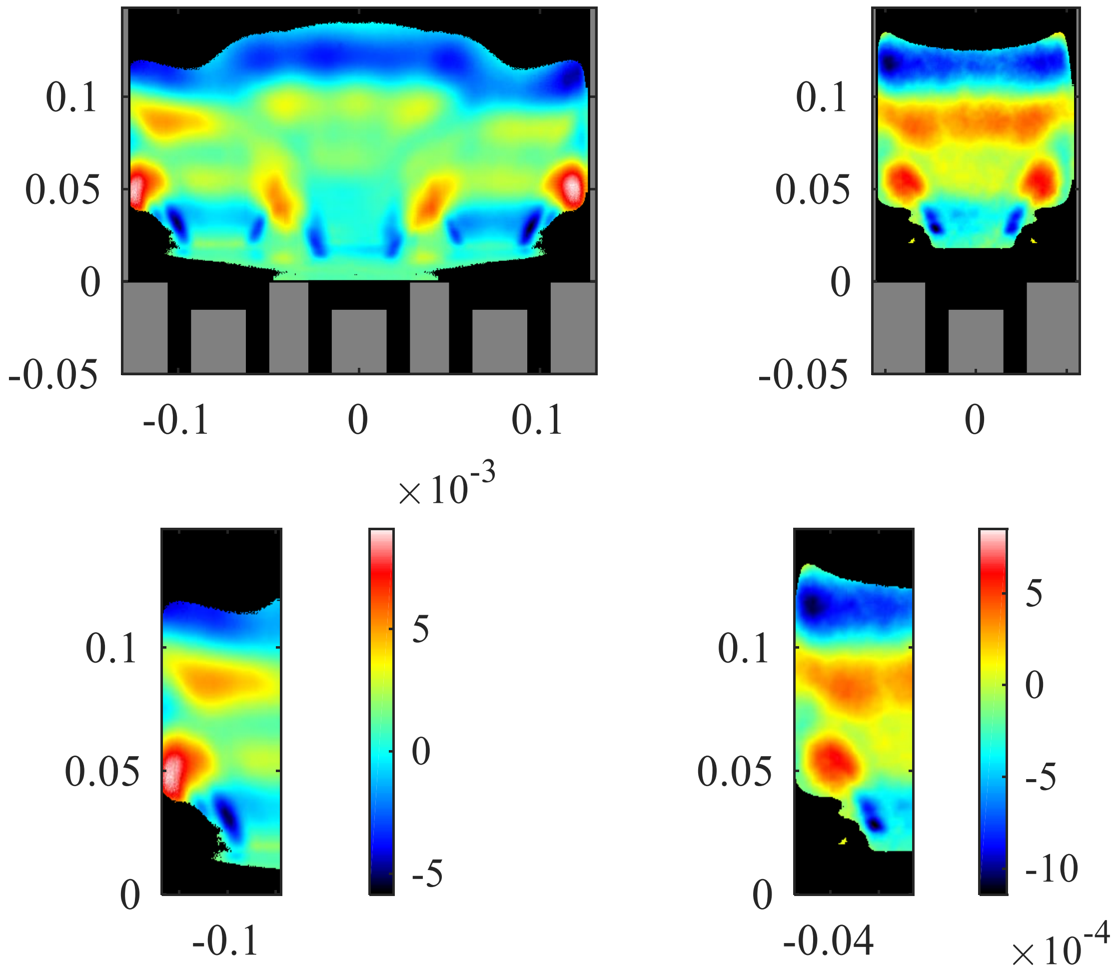
Cropped image:



The fluctuations of the flames are similar under self-excited instability conditions, although with varying severity

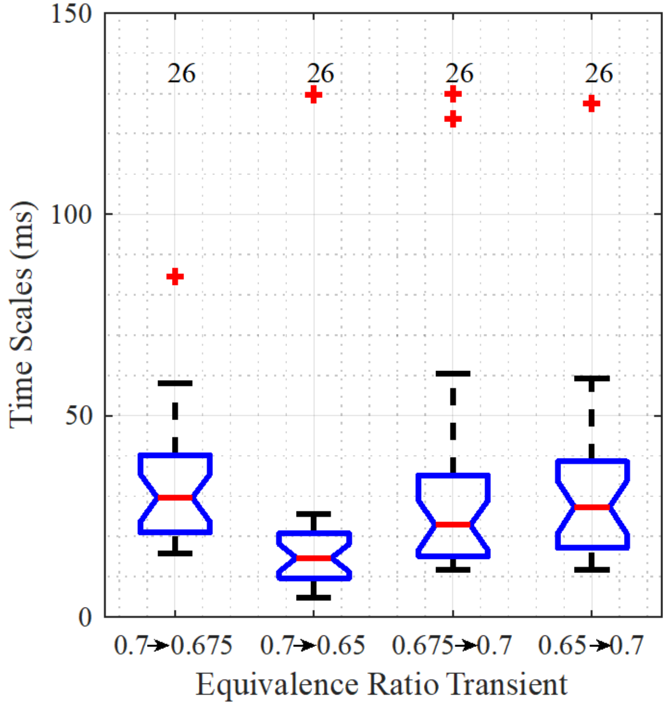


Normalized Rayleigh Index images tell us that the driving in the single-nozzle combustor is much higher, though p' is the same

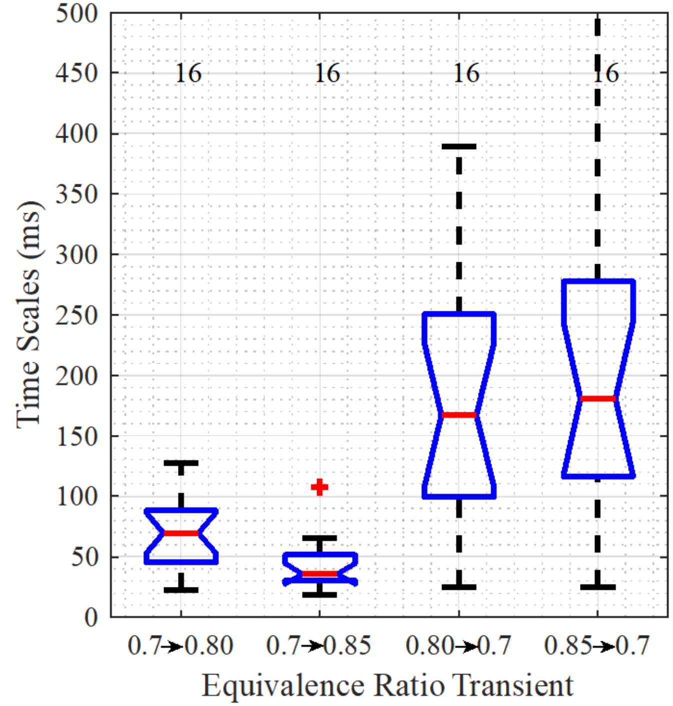


Single-nozzle flames are less sensitive to transient direction and amplitude than multi-nozzle flames

Single-Nozzle Transients



Multi-Nozzle Transients



Work submitted to ASME Turbo Expo:

Chen, X., *Culler, W., Peluso, S., Santavicca, D., O'Connor, J., (2018) "Comparison of equivalence ratio transients on combustion instability in single-nozzle and multi-nozzle combustors," ASME Turbo Expo*

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Wrap-up and Questions

- **Key findings to date**
  - Transient timescales can be divided into two regimes – short and long – and the behavior of the system during the transient is different in each regime
  - Flame interaction likely plays a significant role in instability – both in terms of staging efficacy (axisymmetric vs. non-axisymmetric) and multi-nozzle behavior (as compared to single-nozzle)

- **Next steps**
  - Quantify system damping more quantitatively to understand damping's role in transient behavior
  - Use tomographic imaging and high-speed PLIF to understand the role of flame interaction in dynamical flame behavior

Acknowledgements

— **Penn State:** Dom Santavicca, Bryan Quay, Janith Samarasinghe, Wyatt Culler, Xiaoling Chen, Jackson Lee, Steve Peluso, Ankit Tyagi, Olivia Sekulich

— **GE Global Research:** Keith McManus, Tony Dean, Janith Samarasinghe, Fei Han

— **DOE/NETL:** Mark Freeman

— College of Engineering Instrumentation Grant Program, Mechanical and Nuclear Engineering at Penn State

Questions?

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