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THE AIR FORCE RESEARCH LABORATORY
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Large Eddy Simulations of Transverse Combustion Instability in a Multi-Element Injector

Matt Harvazinski[1], Yogin Desai[2], Doug Talley[1], Venke Sankaran[1]

[1] Air Force Research Laboratory

[2] HyPerComp, Inc.

History

Combustion instability is an organized, oscillatory motion in a combustion chamber sustained by combustion.

CI caused a four year delay in the development of the F-1 engine used in the Apollo program

> 2000 full scale tests

> $400 million for propellants alone (2010 prices)

Irreparable damage can occur in less than 1 second.

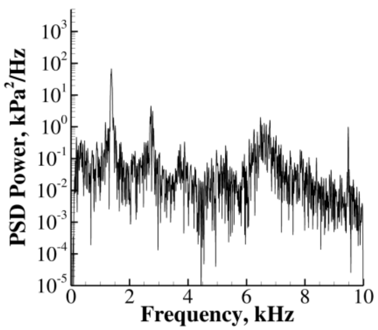
Damaged engine injector faceplate caused by combustion instability

"Combustion instabilities have been observed in almost every engine development effort, including even the most recent development programs"

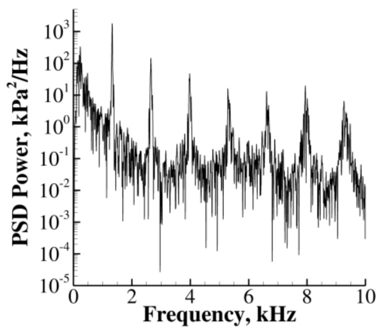
– JANNAF Stability Panel Draft (2010)

Single Element Studies

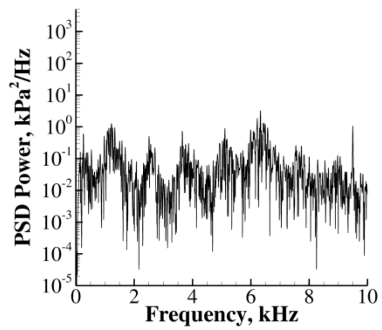
Short Post
Marginally Stable



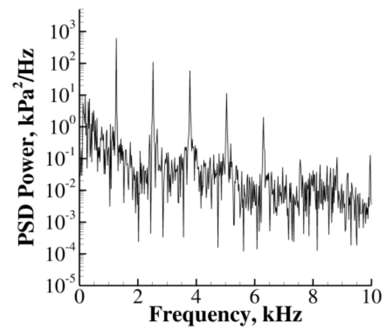
Intermediate Post
Unstable



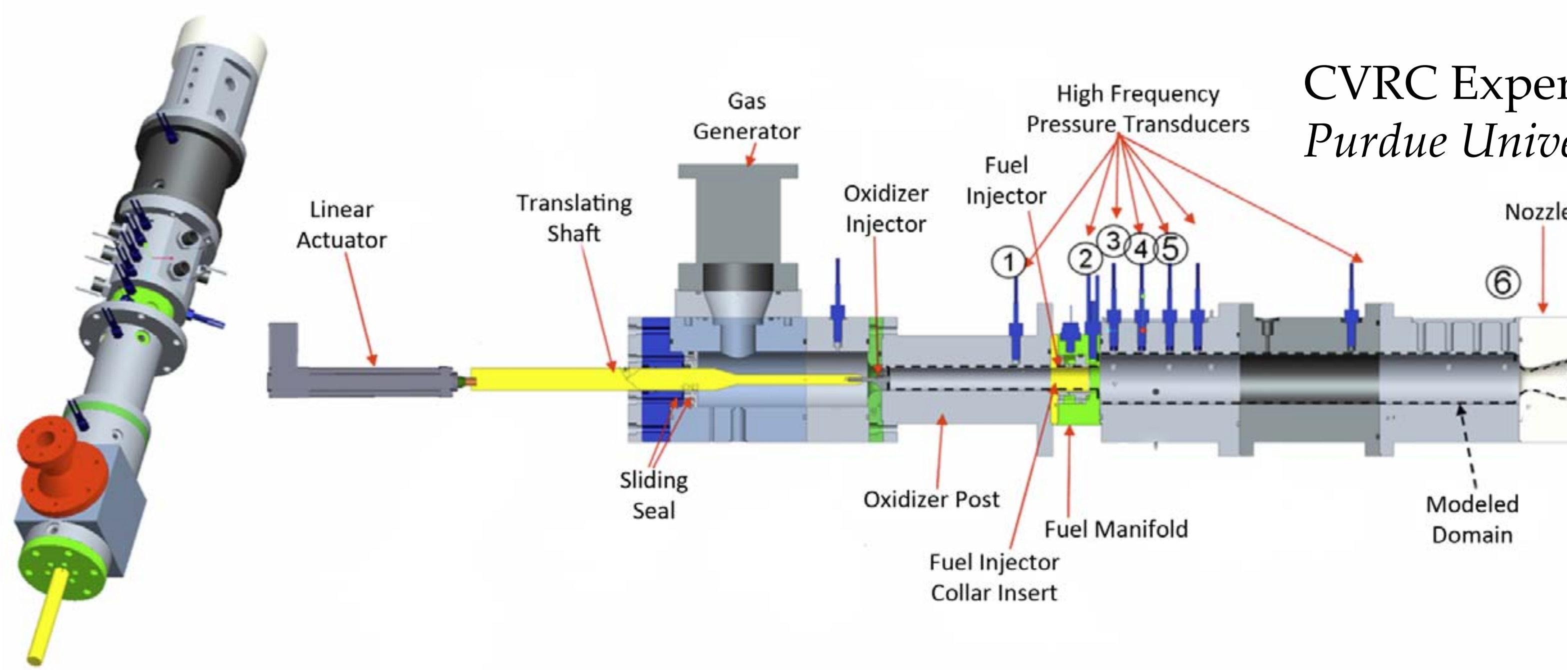
Long Post
Stable



Long Post
Unstable

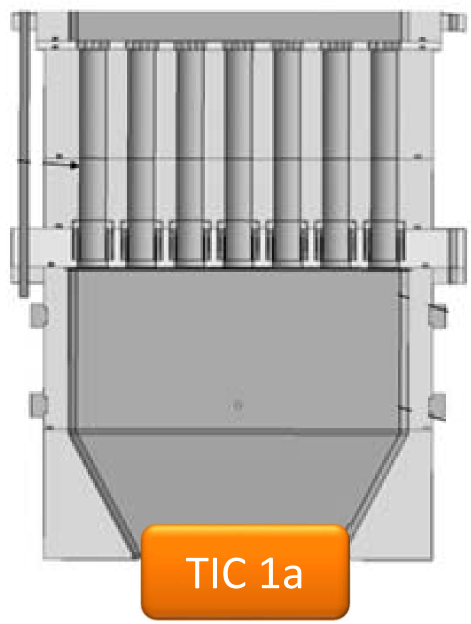


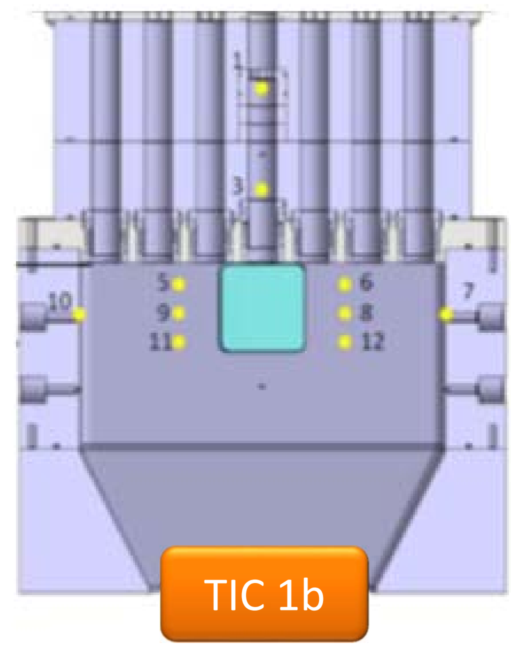
CVRC Experiment
Purdue University



Transverse Instability Combustor

- Transverse Instability Combustor – TIC
- Experimental rig developed at Purdue University
- Four major iterations to date
- Rectangular chamber with 7 elements
- Linear array of 7 elements
- Injectors are similar to the single element work
- Instability is self-excited





Single & Multi-element Studies

Single Element

- Less expensive
- Smaller domains

- Substantial work published

- Wall effect is exaggerated

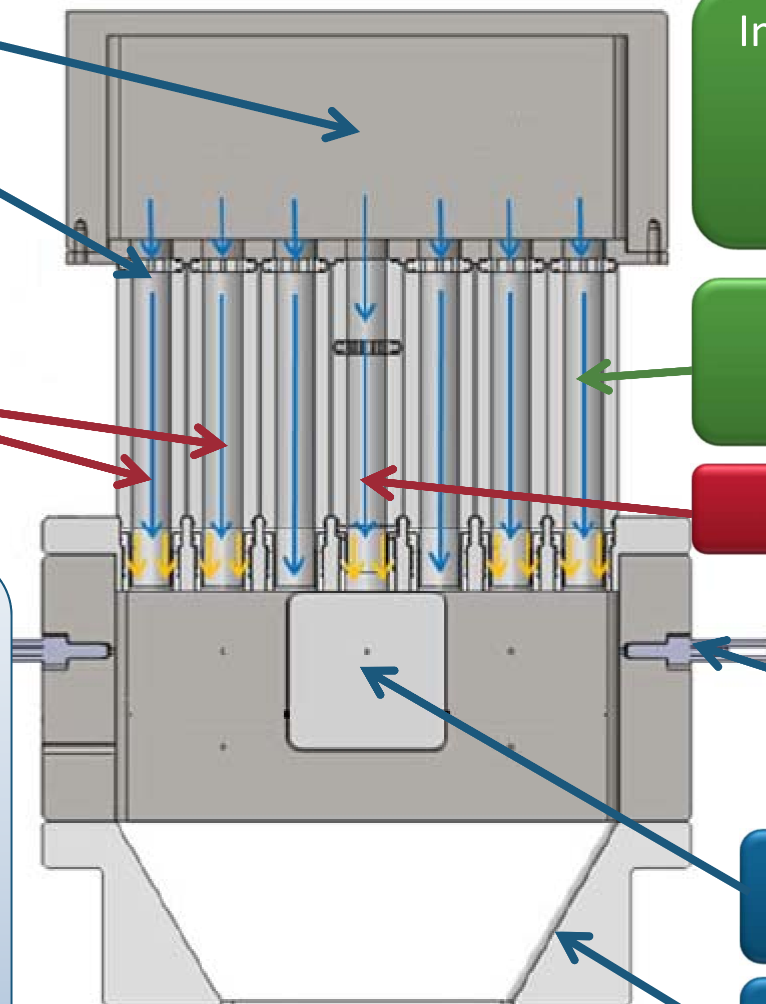
Multi-element

- More expensive
- Larger domains
- Complex geometries

- Less literature, limited work

- Captures inter-element interactions

TIC Configuration



Dual Purpose Experiment:

1. Self-excited transverse instability

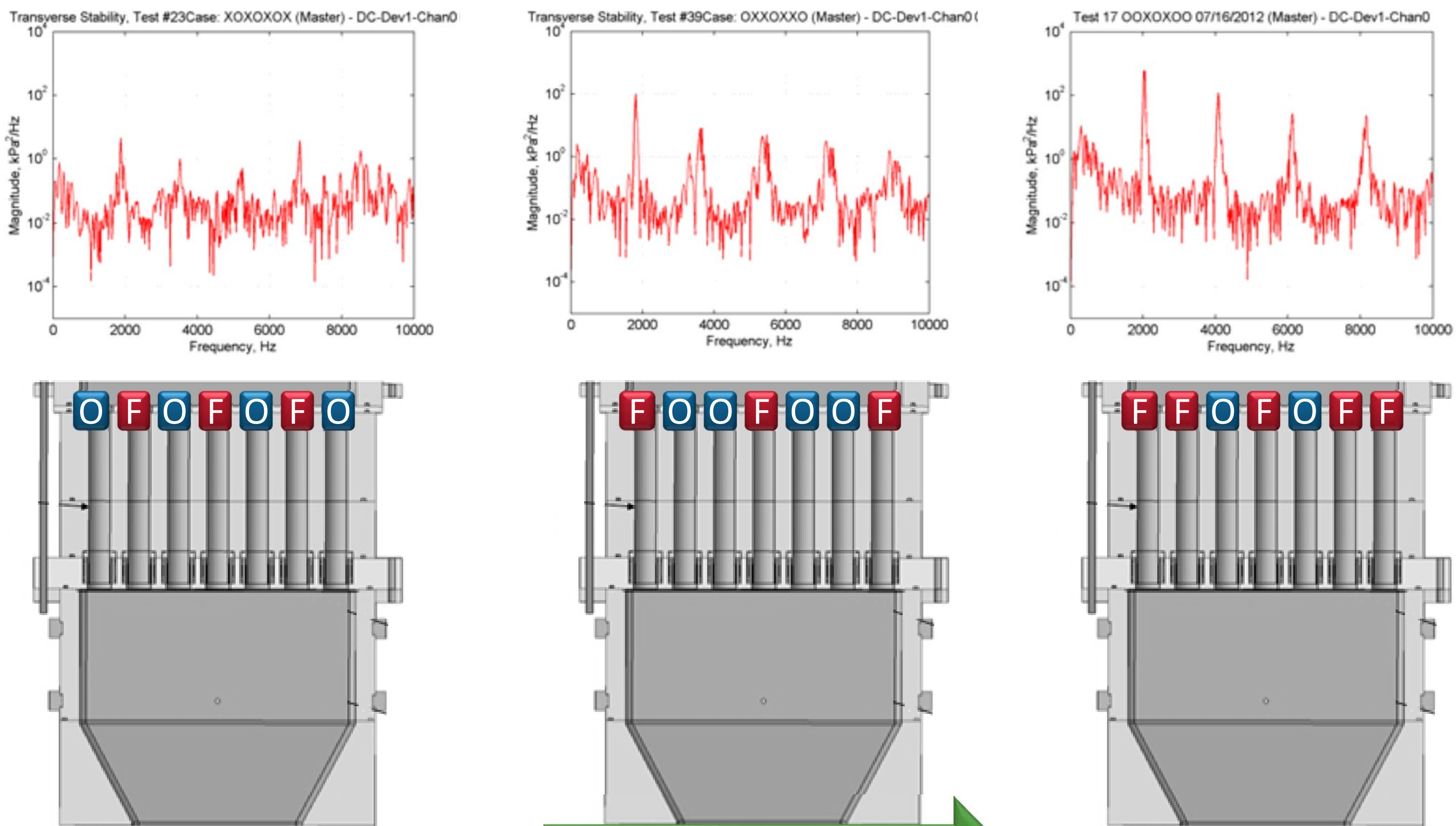
2. Observe combustion response of the study element to high amplitude transverse instabilities

TIC Experiments

		TIC 1a	TIC 1b	TIC 1c	TIC 1d
Oxidizer		H_2O_2	H_2O_2	H_2O_2	H_2O_2
Fuel	Driving	JP-8	RP-1	CH_4	CH_4
	Study	$C_{12}H_{26}$	C_2H_6	CH_4	CH_4
Oxidizer Inlet	Driving	Perforated Plate	Perforated Plate	Perforated Plate	Choked Venturi
	Study	Perforated Plate	Choked Slots	Choked Slots	Choked Venturi
Notes		Two-phase flow		Multiple study ox-post lengths considered	Multiple ox-post lengths considered
Companion Simulations			3-element	3 & 7-element	

This Study

Amplitude Control – TIC 1a&b



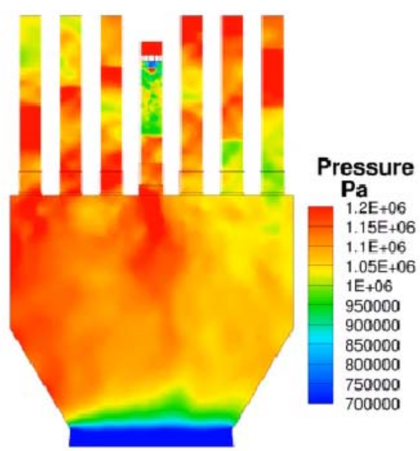
Increasing Amplitude

F - Fuel & Oxidizer
O - Oxidizer Only

Two Distinct Modeling Approaches

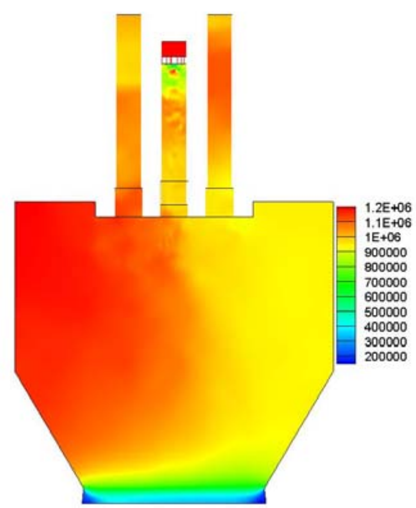
Full Simulation

- Captures self-excited instability
- Captures inter-element interactions
- Amplitude is difficult to control
- Expensive



Reduced Model

- Does not capture driving
- Limited inter-element interactions
- Amplitude is prescribed
- Low cost



Test Configurations

	Configuration 1	Configuration 4
	Unstable	**Stable**
Injector Setup	F F O F O F F	O F O F O F O
p' (%p_c)	65	8
p', kPa	620	70
1W Frequency, Hz	2032	1855

Outer driving injectors flow RP1, center study element flows C_2H_6

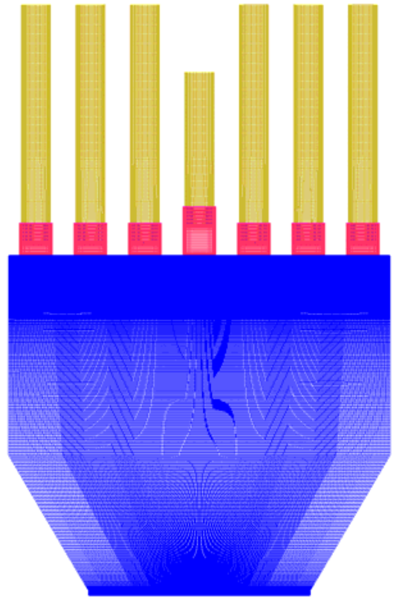
Oxidizer is decomposed hydrogen peroxide, 58% H_2O, 42% O_2

	Temp., K	Mass Flow, kg/s
Oxidizer	1029	0.196
RP1	298	0.033
C_2H_6	319	0.025

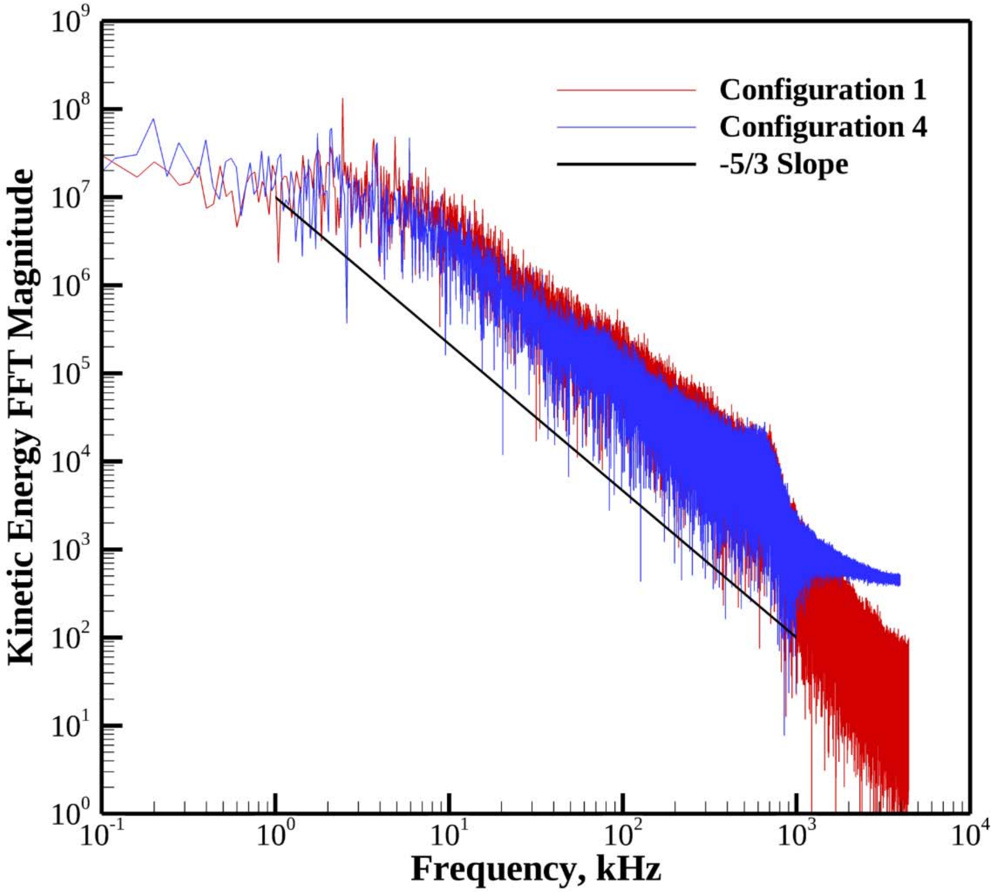
Simulation Details

- **Multi-block structured mesh, 15.63 M**
- **LESLIE – reacting flow LES code**
- **RP1 is modeled as $C_{10}H_{22}$**
- **Specified mass flow inlets (reflecting)**
- **Finite rate kinetics**

$$C_2H_6 + \tfrac{5}{2}O_2 \longrightarrow 2\,CO + 3\,H_2O$$
$$C_{10}H_{22} + \tfrac{21}{2}O_2 \longrightarrow 10\,CO + 11\,H_2O$$
$$CO + \tfrac{1}{2}O_2 \longrightarrow CO_2$$
$$CO_2 \longrightarrow CO + \tfrac{1}{2}O_2$$



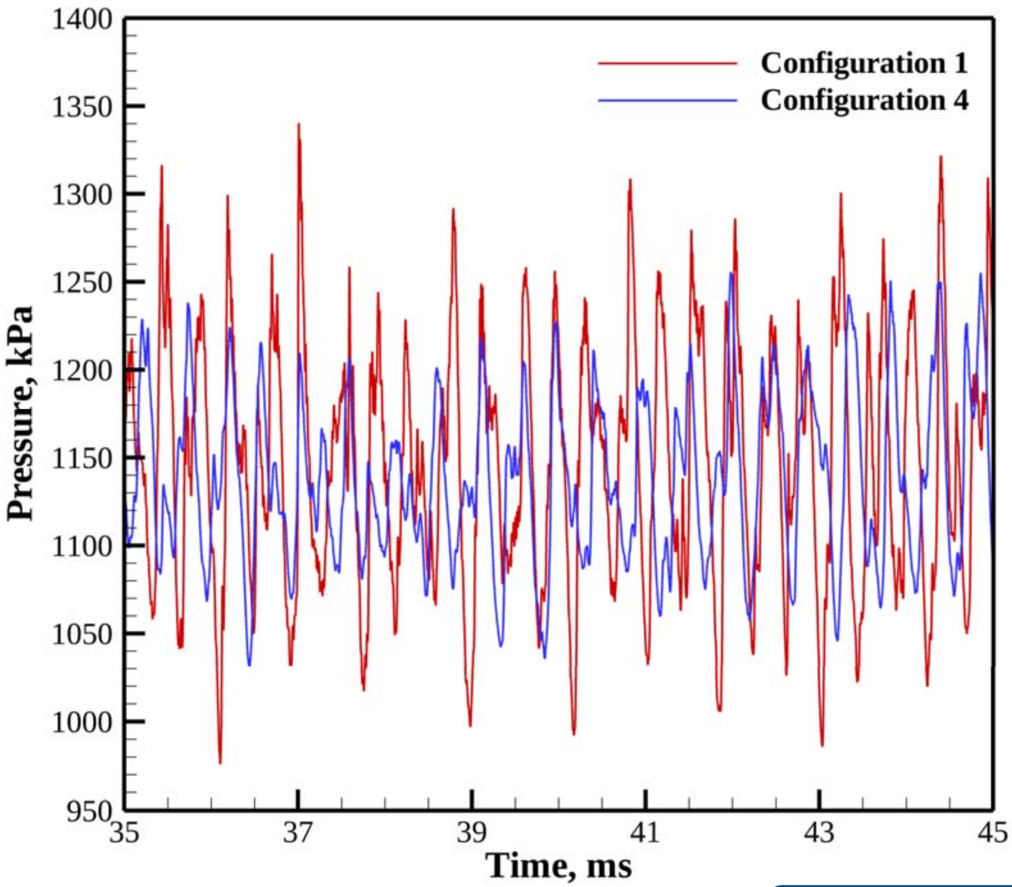
Turbulent Spectrum



The KE spectrum is used to help assess the grid resolution

Good Agreement with the -5/3 slope for both cases

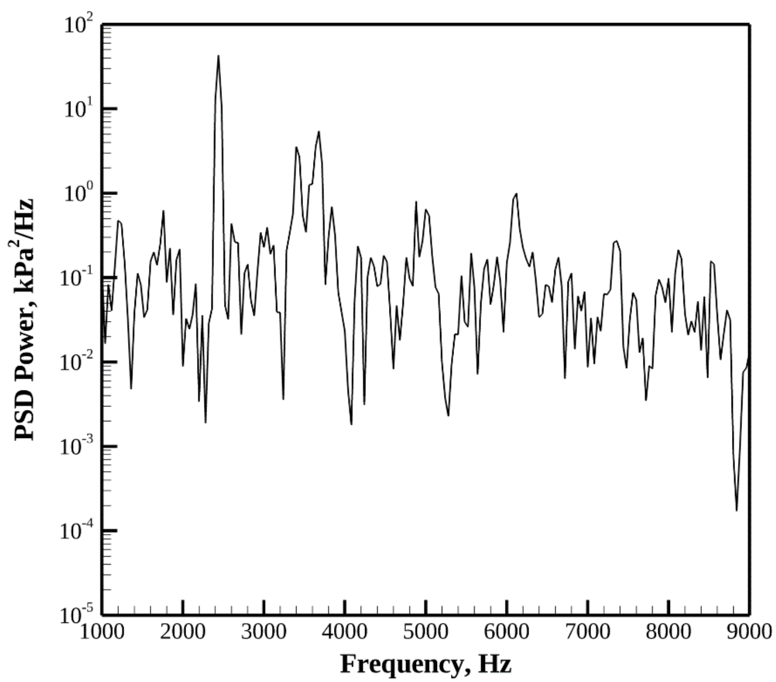
Side Wall, Pressure



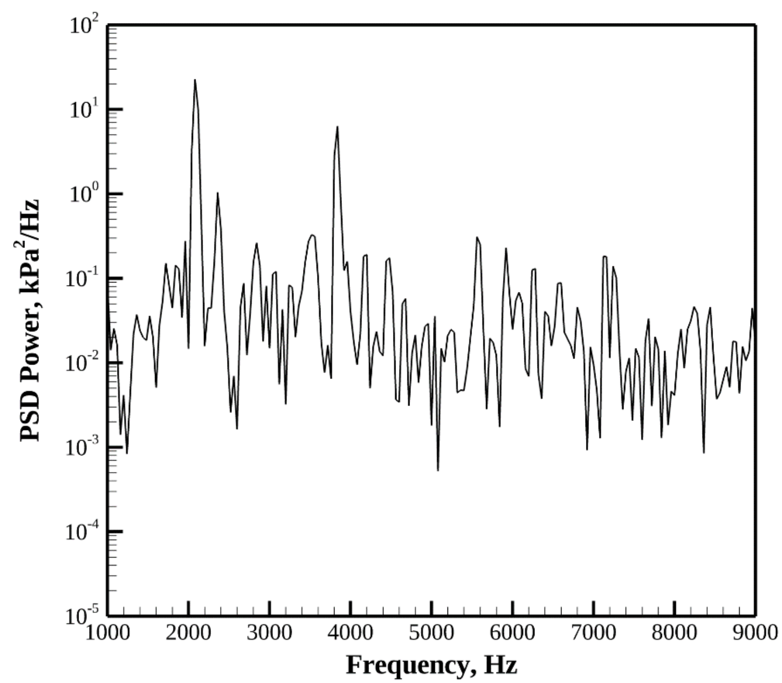
Similar amplitudes

Side Wall, PSD

Unstable



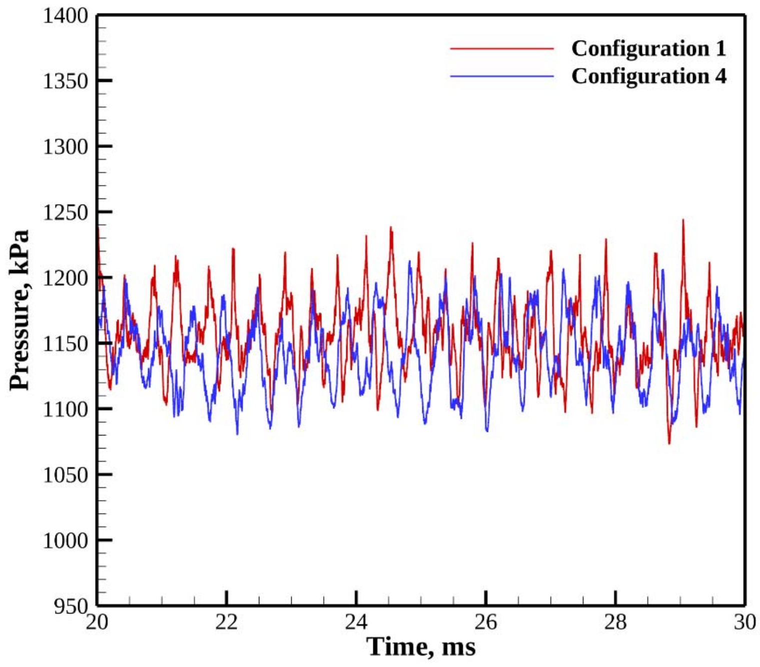
Stable

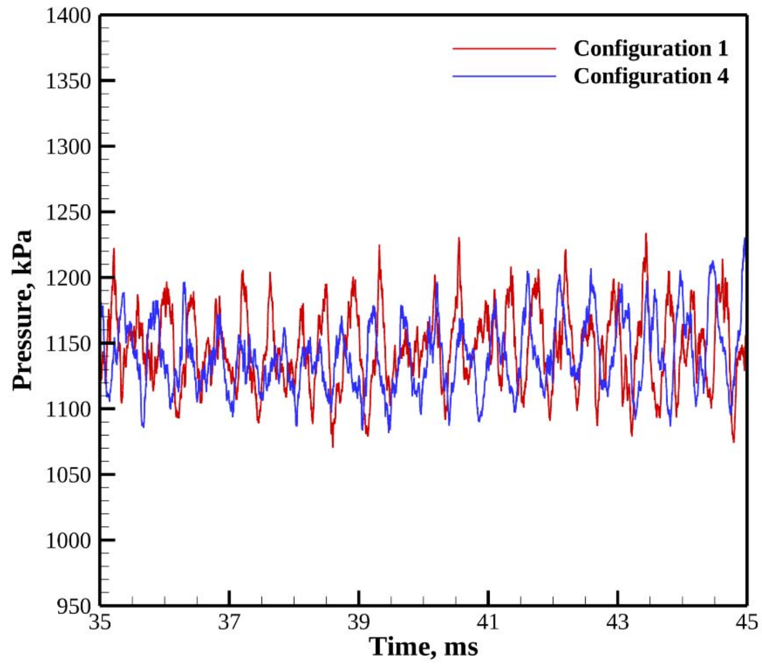


Bifurcated second harmonic, the frequency is less than the twice the first mode frequency

Well defined second harmonic at twice the first mode frequency

Chamber Center, Pressure

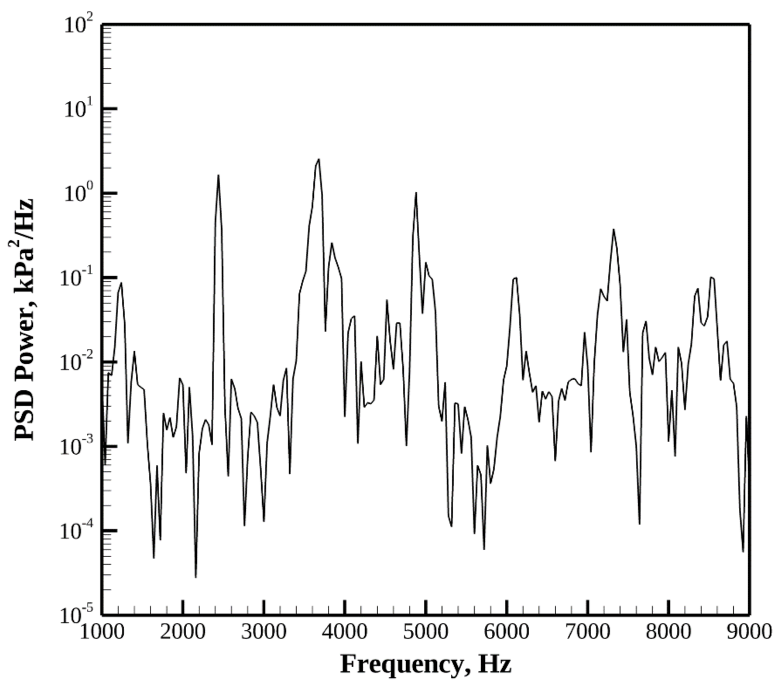




Lower amplitudes compared with the side wall, consistent with a pressure node of the 1W mode.

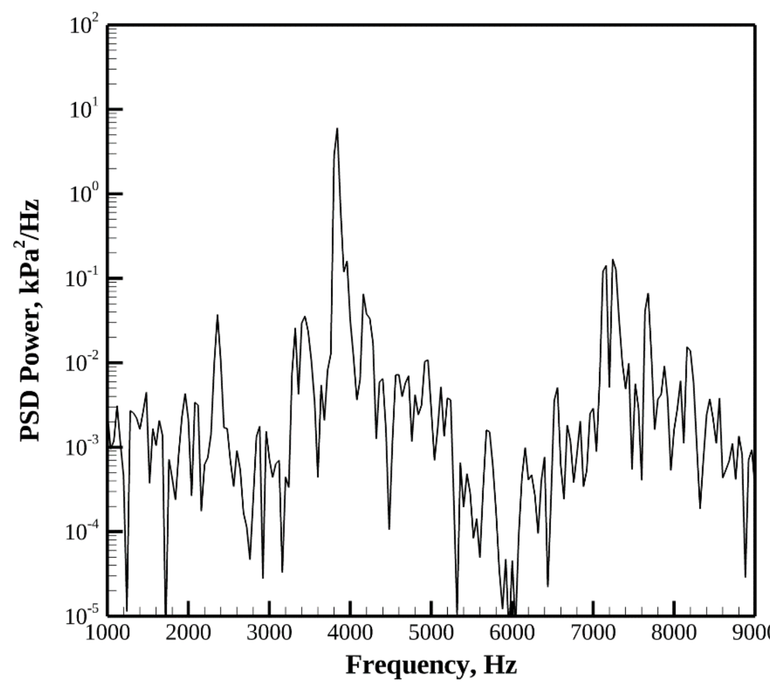
Chamber Center, PSD

Unstable



Excited 1W and 2W, not consistent with a transverse mode

Stable



Excited 2W, consistent with a transverse mode

PSD Summary

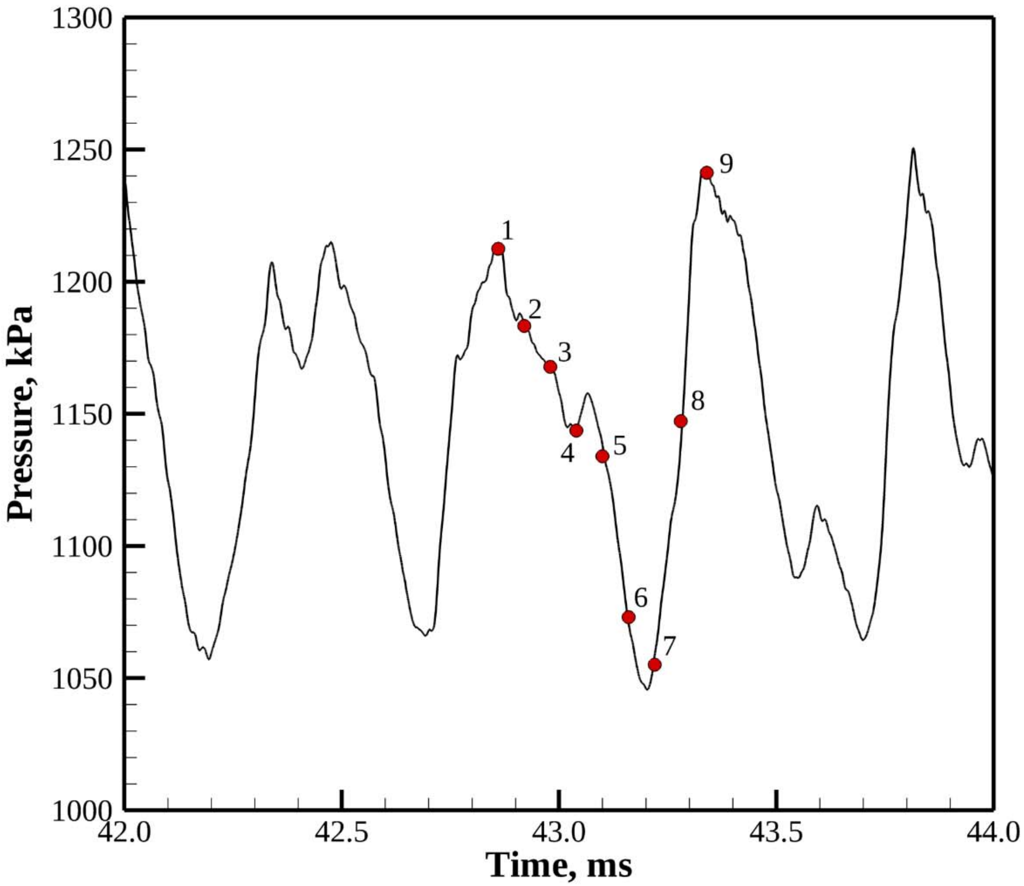
	Experiment	Simulation
Configuration 1		
1W Frequency, Hz	2032	2440
p', kPa	620	259
p_c, kPa	965	1148
p'/p_c	65%	23%
Configuration 4		
1W Frequency, Hz	1855	2080
p', kPa	70	139
p_c, kPa	815	1139
p'/p_c	8%	12%

Predicted amplitude for the unstable case is too low, PSD analysis indicates that it may not be a transverse instability

Amplitude prediction for the stable case is of the same order of magnitude.

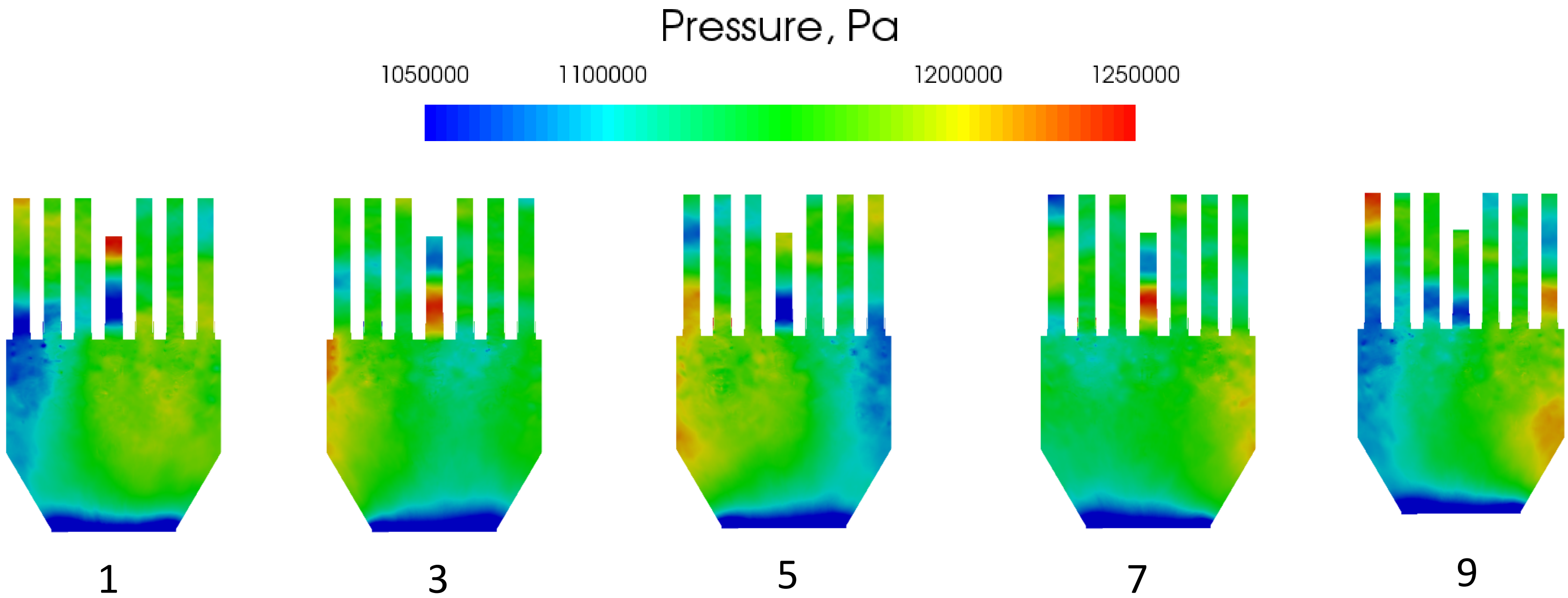
In both cases the chamber pressure and frequency are too high

Stable Configuration



Point of analysis for a single representative cycle

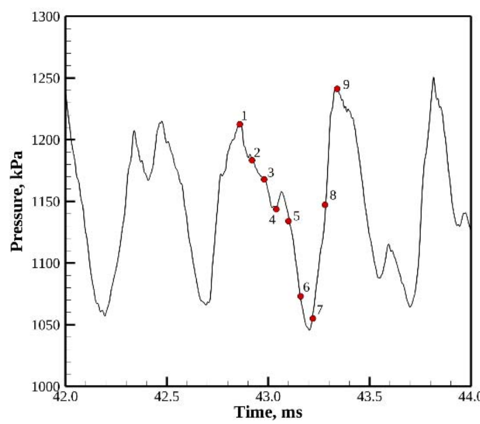
Unsteady Pressure



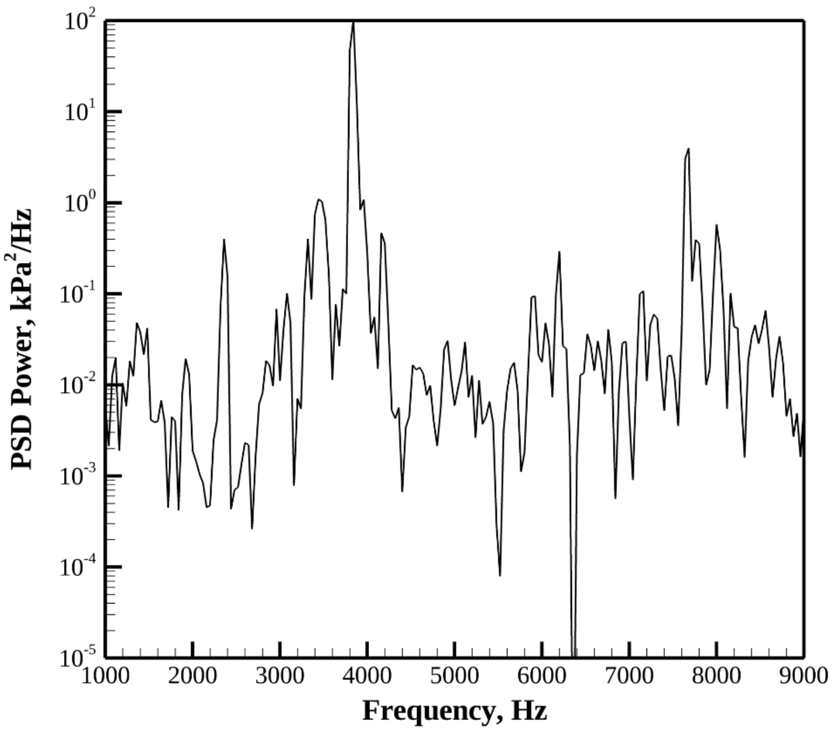
Transverse mode in the chamber

Longitudinal modes are setup in the injectors

Center element (located at 1W node) shows excitation



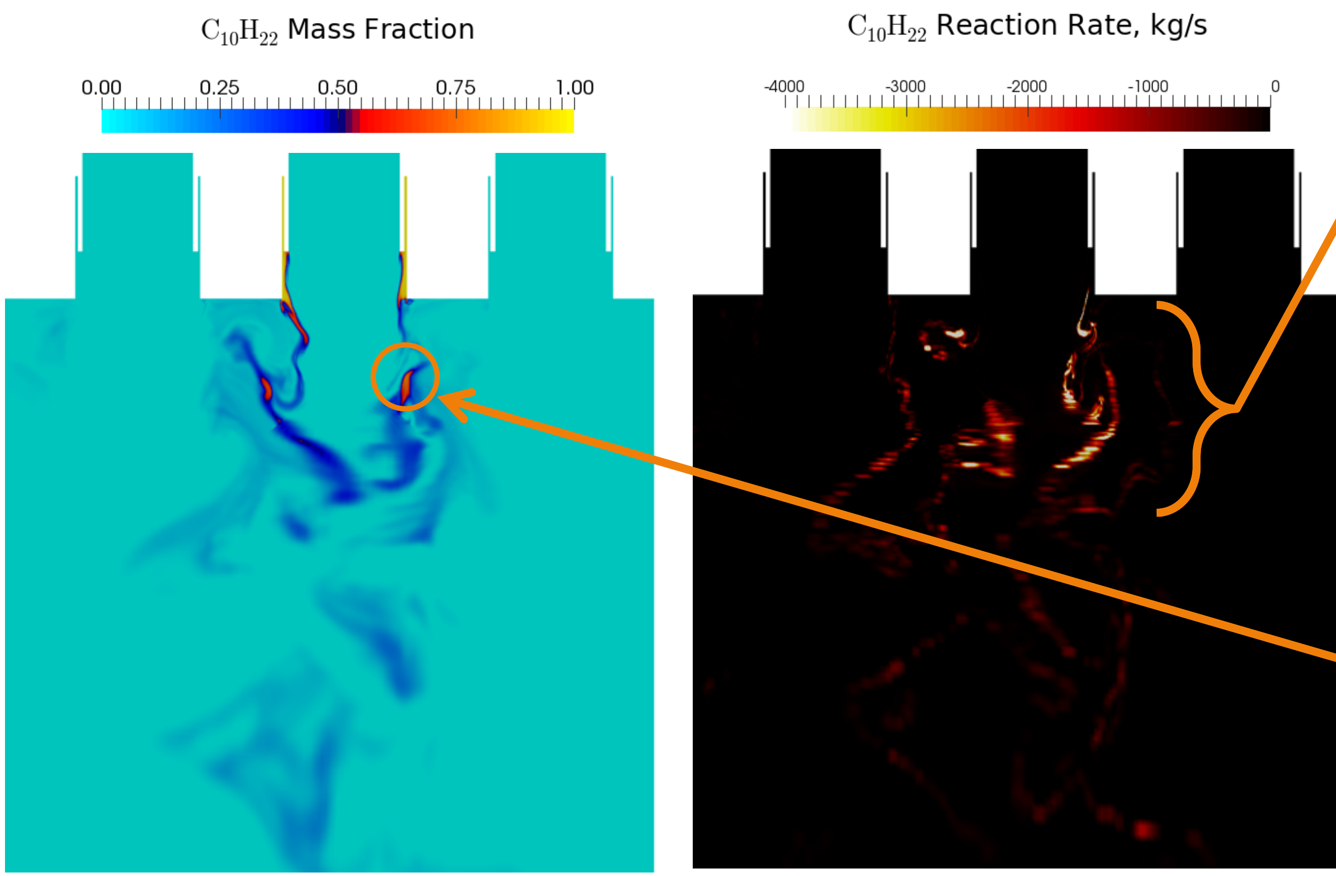
Center Element PSD



The center element is responding to the 2W frequency.

The amplitude of the response is larger than the 2W response in the chamber

Driving Elements



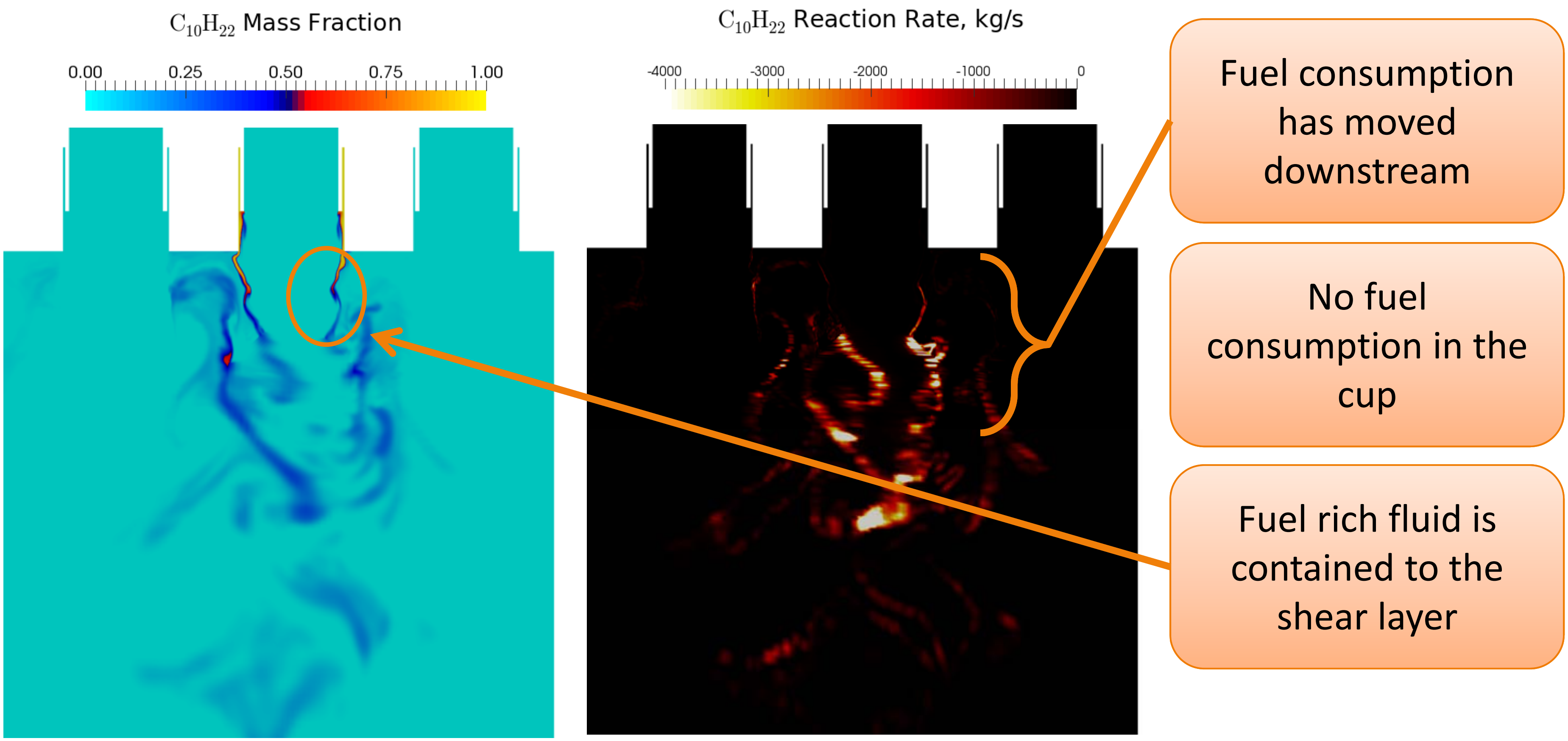
Fuel consumption close to the injector plate

Small amounts of fuel consumption in the cup

Pockets of fuel rich fluid away from the injector plate

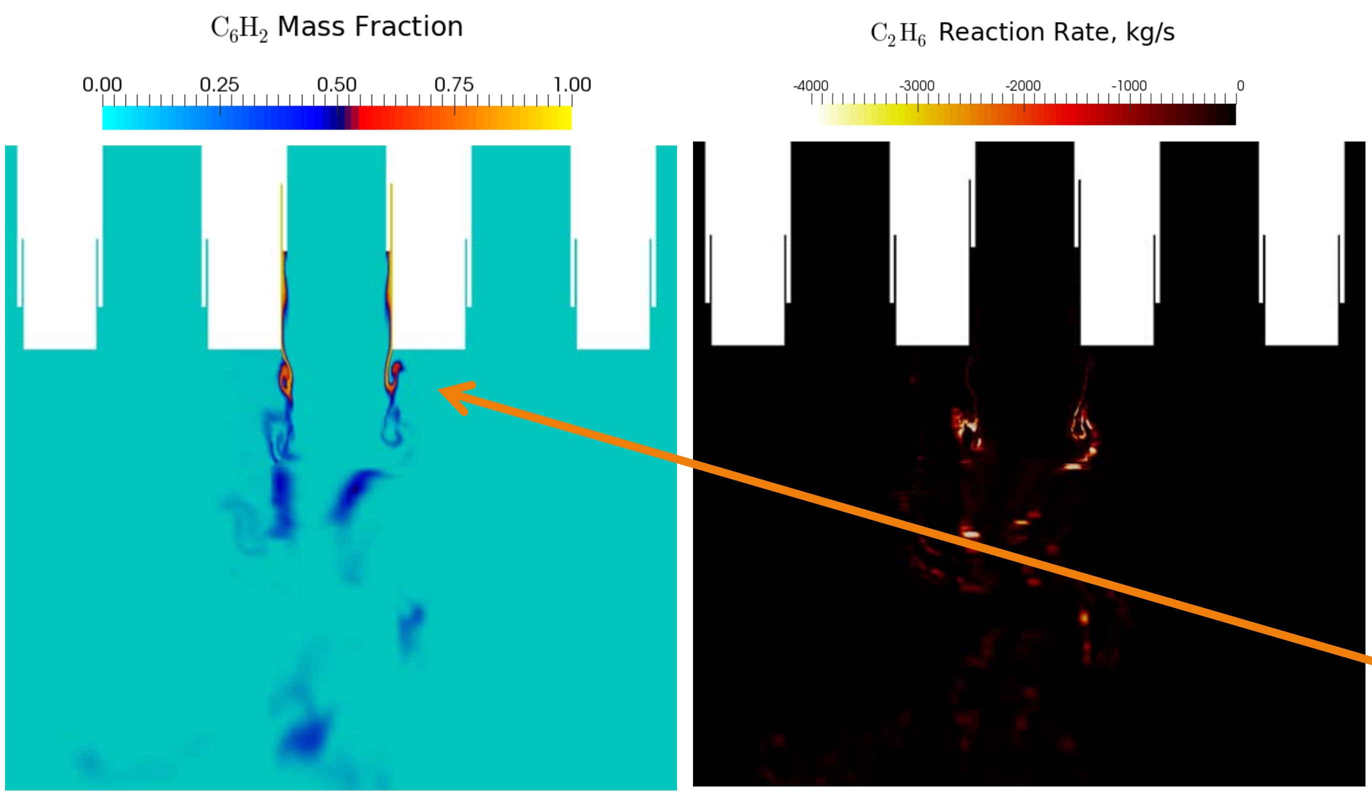
Time 5 – low pressure on the right side of the chamber

Driving Elements



Time 8 – high pressure on the right side of the chamber

Study Element



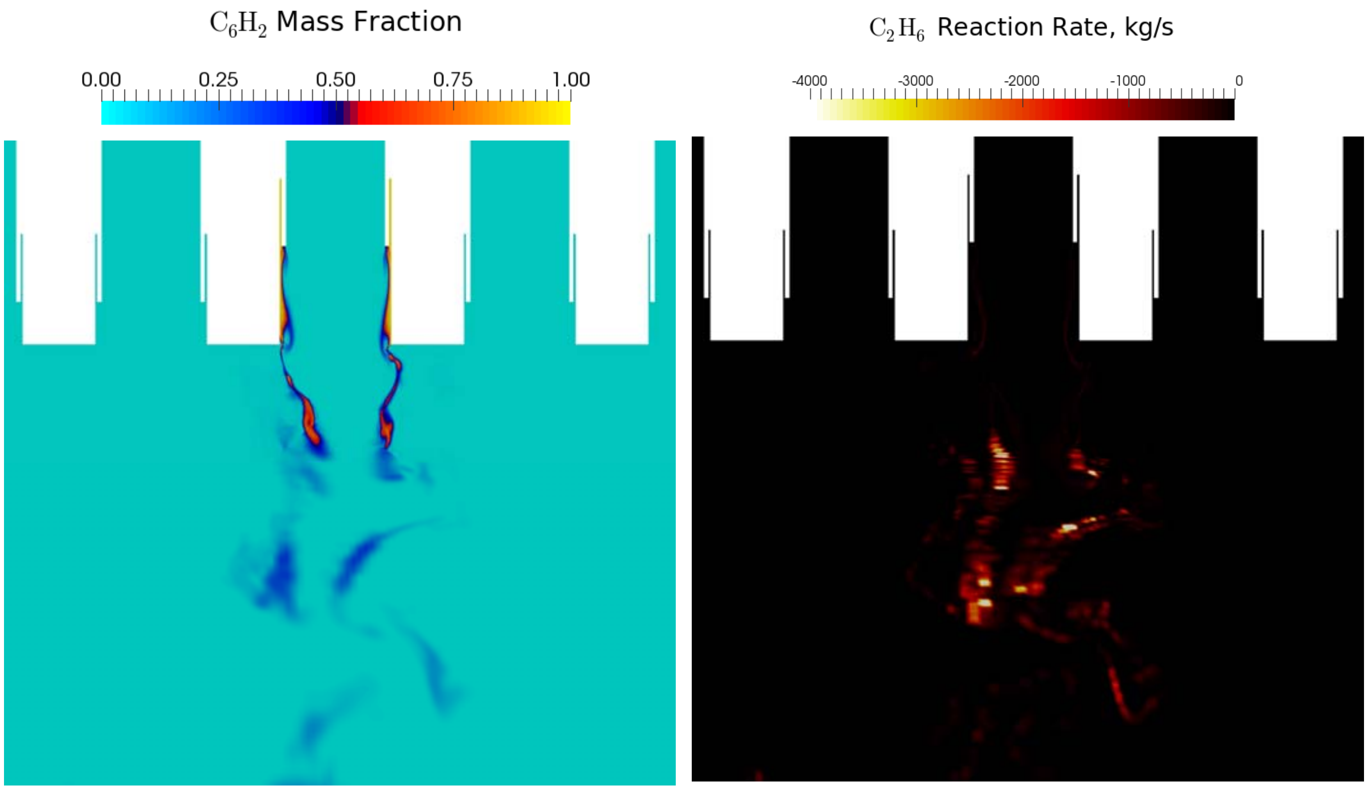
Detached flame

No burning in the cup region

Pockets of fuel rich fluid away from the injector plate

Time 5 – low pressure in the center element

Study Element



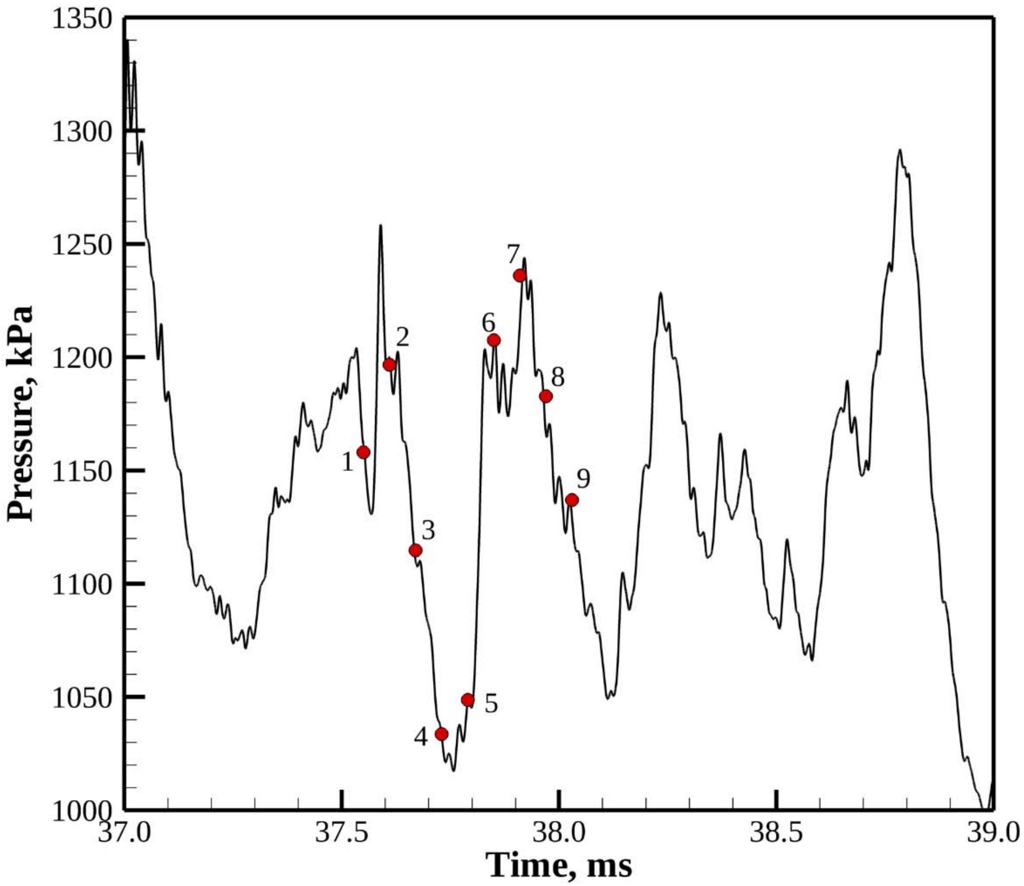
Flame remains detached

No burning in the cup region (unlike single element studies)

Pockets of fuel rich fluid away from the injector plate remain

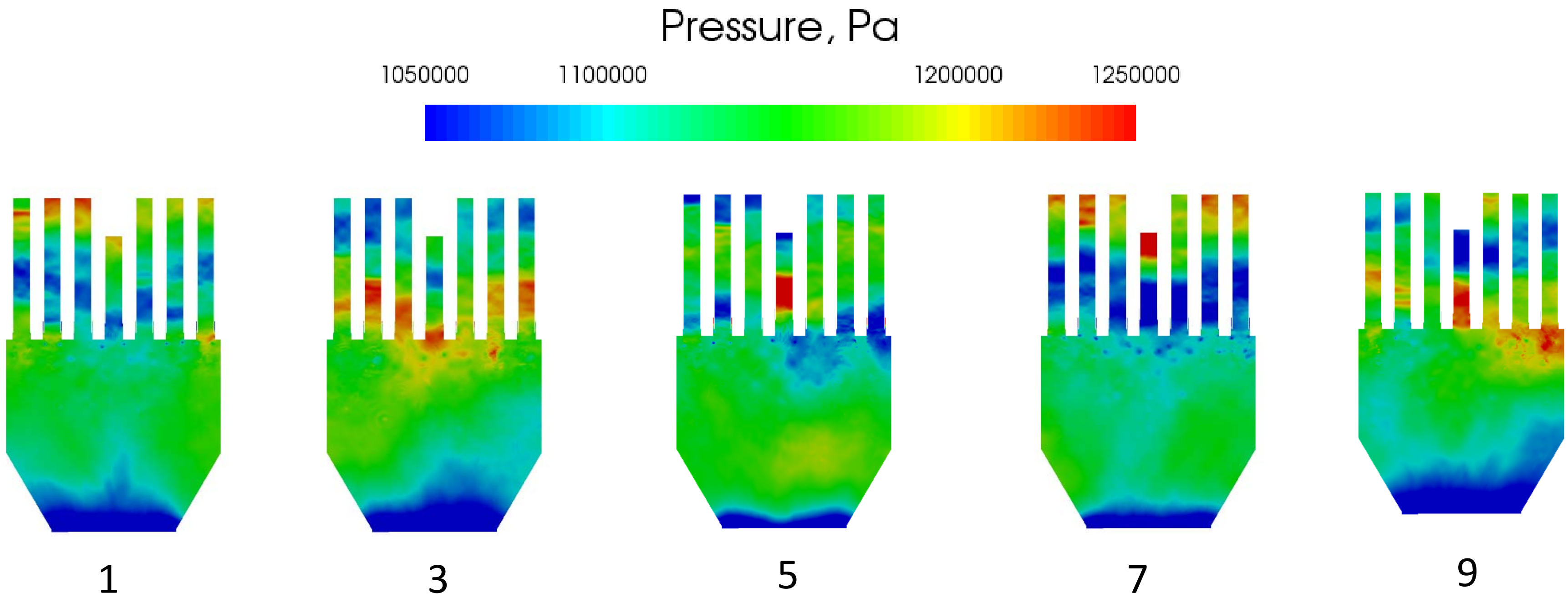
Time 7 – high pressure in the center element

Unstable Configuration



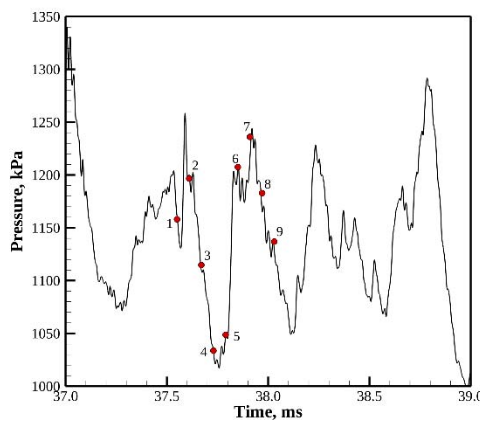
Point of analysis for a single representative cycle

Unsteady Pressure

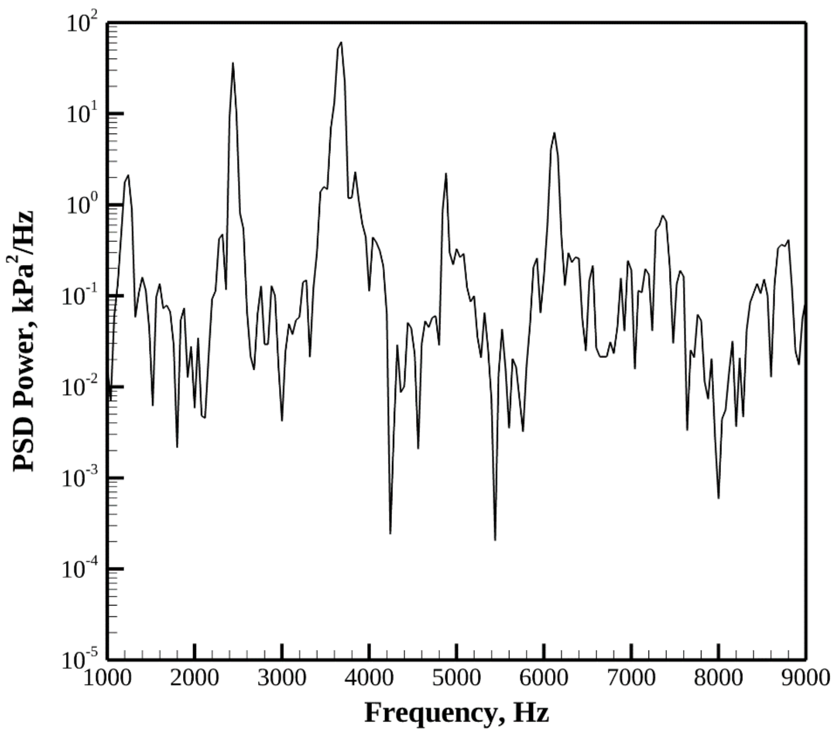


Week transverse mode in the chamber (near the injector plate only)

All injector elements are excited



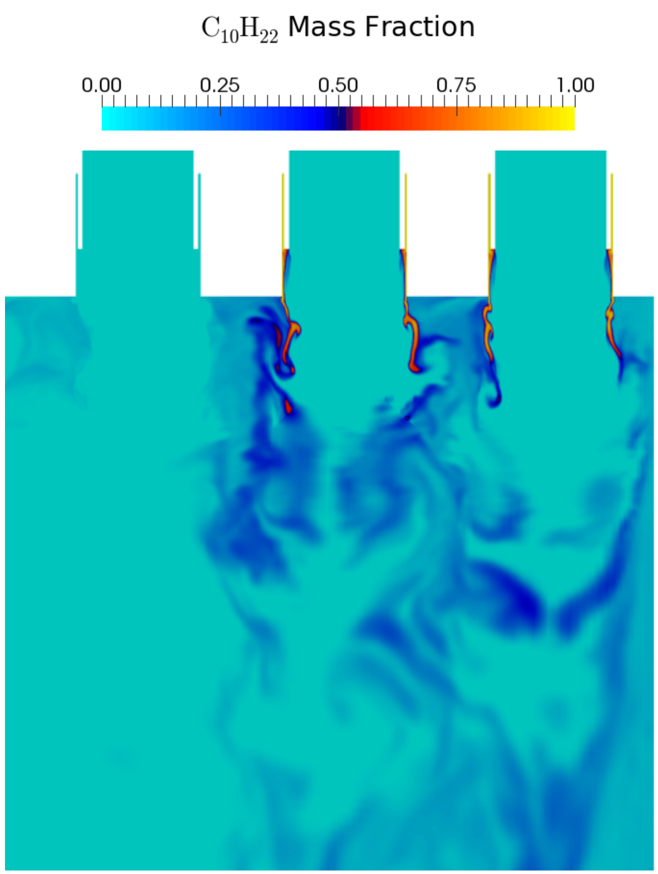
Center Element PSD

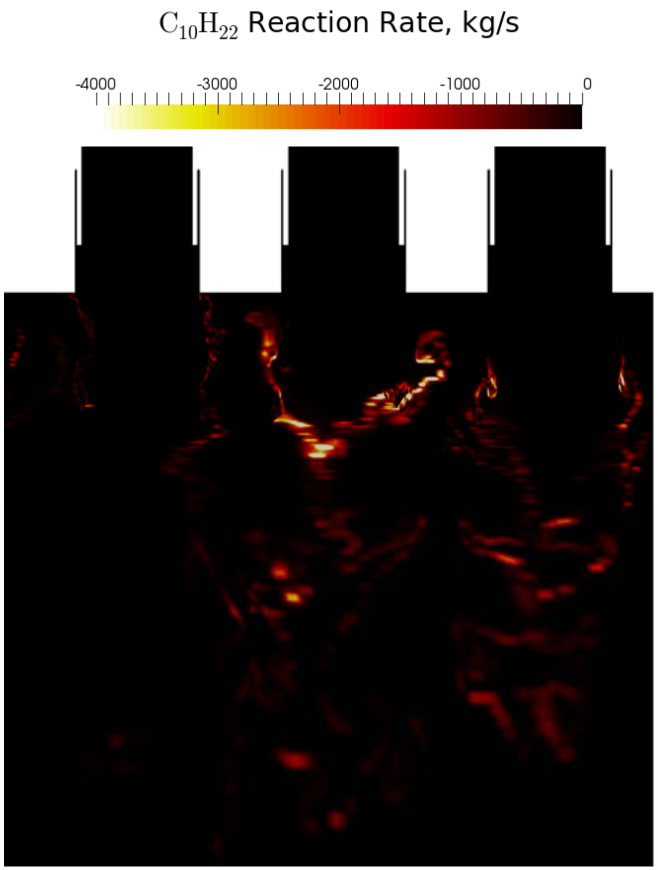


The center element is responding to the 1W and 2W frequencies.

The amplitude of the response is larger than the 1W and 2W responses in the chamber

Driving Elements



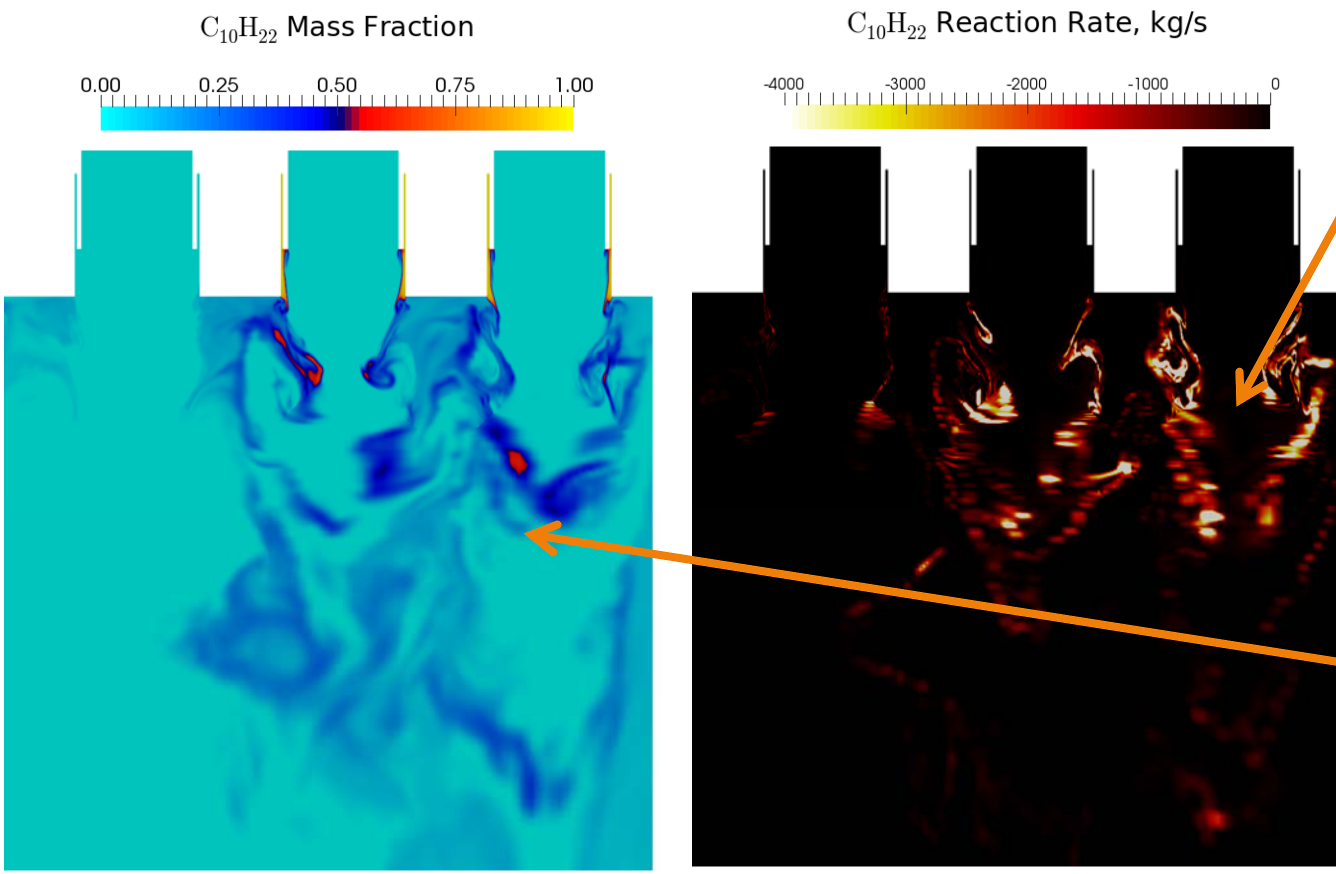


Consumption rates of the two driving injectors is different

Larger quantities of fuel are present in the outside injector

Time 5 – low pressure on the right side of the chamber

Driving Elements



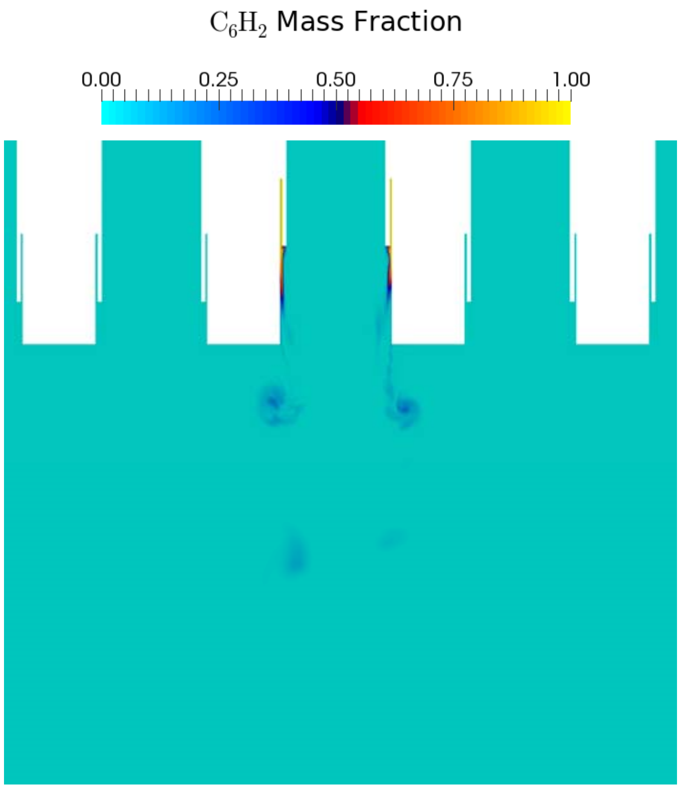
Fuel consumption amplified at high pressure

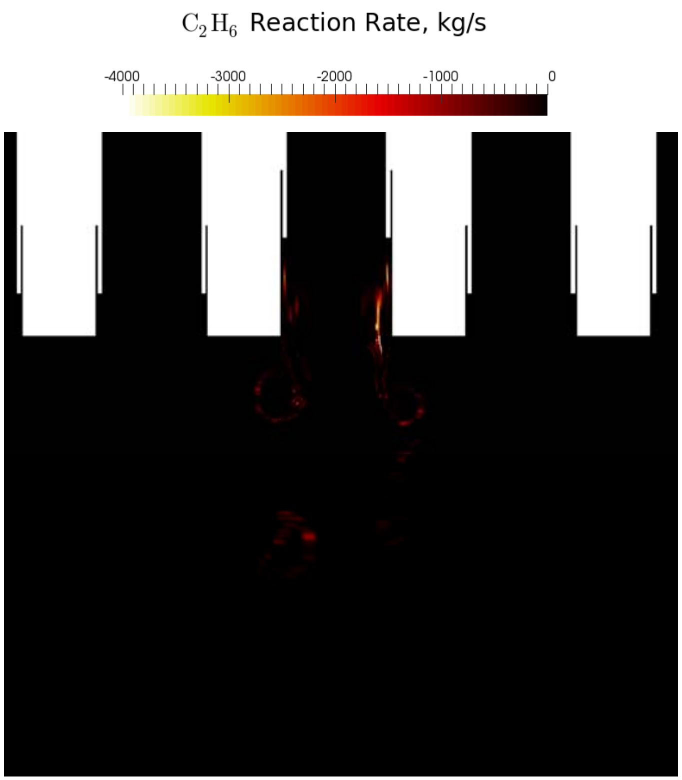
Small consumption of fuel in the cup region

Significant unburned fuel present

Time 9 – high pressure on the right side of the chamber

Study Element



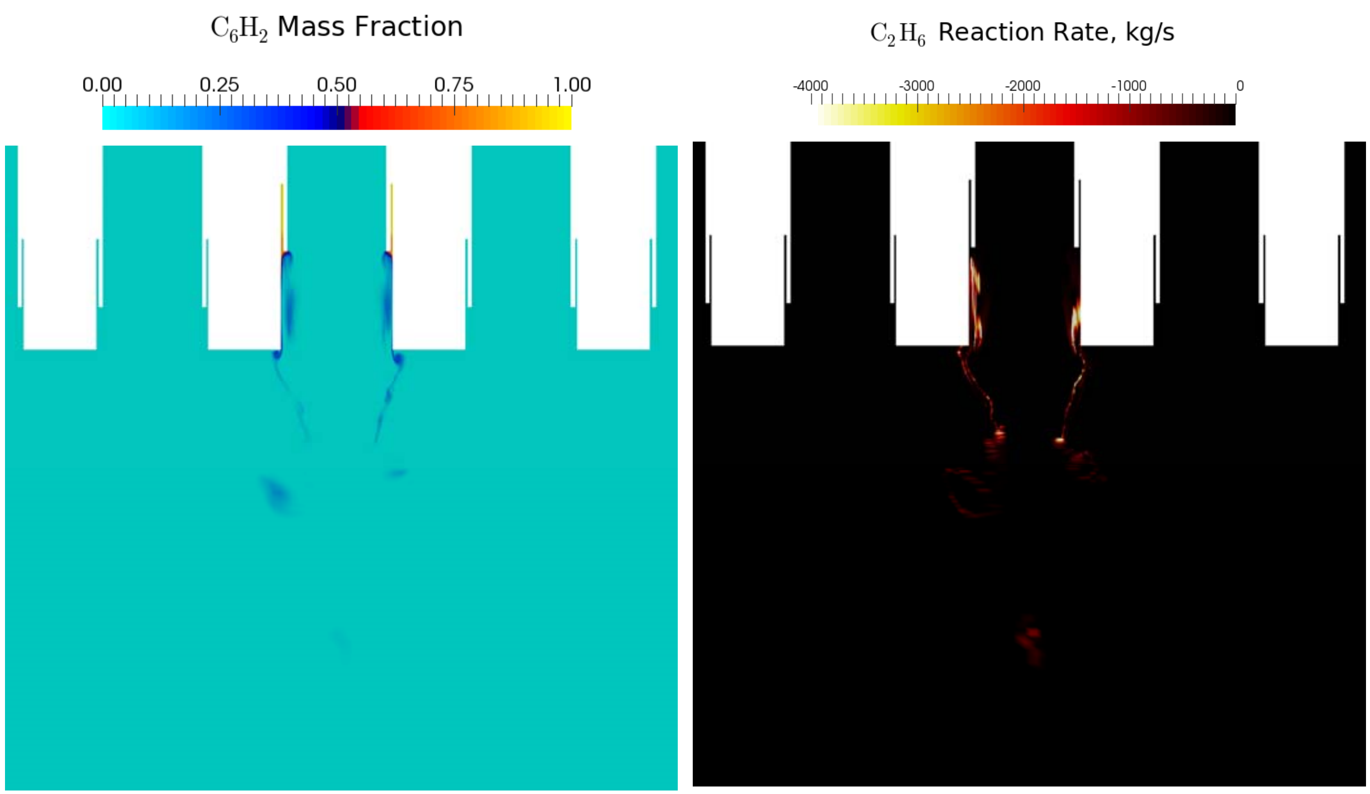


Burning inside the cup region

Very little fuel present the combustor

Time 6 – low pressure in the center element

Study Element



Majority of burning is inside the cup

Very little fuel present the combustor

Very different from case 4 which showed a detached flame

Time 4 – high pressure in the center element

Summary

- **Reasonable agreement between the experiment and simulation for the stable case**
  - Different injector response mechanism than was observed in single element studies
- **Unstable configuration did not have a good agreement**
  - Lack of a transverse wave
- **Very different behavior of the center element for the two cases**
  - Case 1 – burning in the cup, responding to 1W and 2W mode
  - Case 4 – detached flame, responding to the 2W mode

Summary

- **Instability mechanism present in the single element longitudinal studies were not present in either case.**

- **Future Work, Look at:**
  - Ideal gas assumption for RP1
  - Grid resolution, flame was further downstream from the injector than single element studies, the grid may have been too coarse in that region