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The importance of hydrodynamics on the initiation of thermoacoustic oscillations:
Transient and Limit Cycle Thermoacoustic Oscillation Dynamics in a Lean Premixed Swirl Stabilized Combustor

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Mechanical Engineering Department

Workshop on Analytical methods in thermo- and aero- acoustics

University of Keele

11 March 2020

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Outline

- Introduction to Thermoacoustic instabilities – Link to Rayleigh Criterion
- Experimental approach used for the physical understanding of the problem
- Interpretation of what triggers the Thermoacoustic instabilities
- Interpretation of how Thermoacoustic instabilities perpetuate

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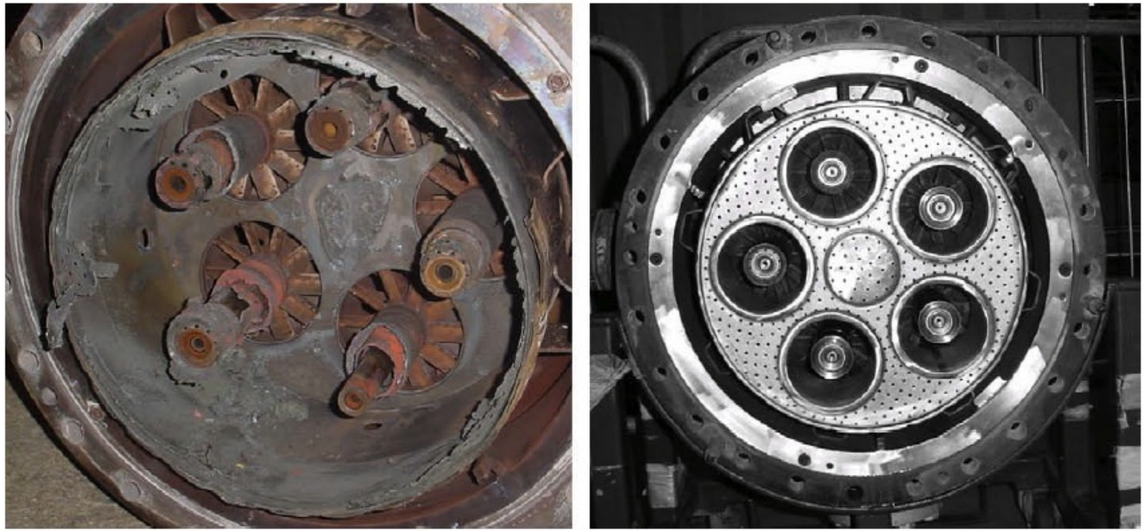
Combustion Instabilities



Burner assembly damaged by combustion instabilities (left). New assembly (right). Goy et al. 2005

- The lean premixed mode of operation is employed for land-based Gas Turbine power generation in order to reduce NO_x emissions.

- Unfortunately the lean premixed mode of operation makes combustors susceptible to the triggering of combustion instabilities, in the form of thermoacoustic oscillations.

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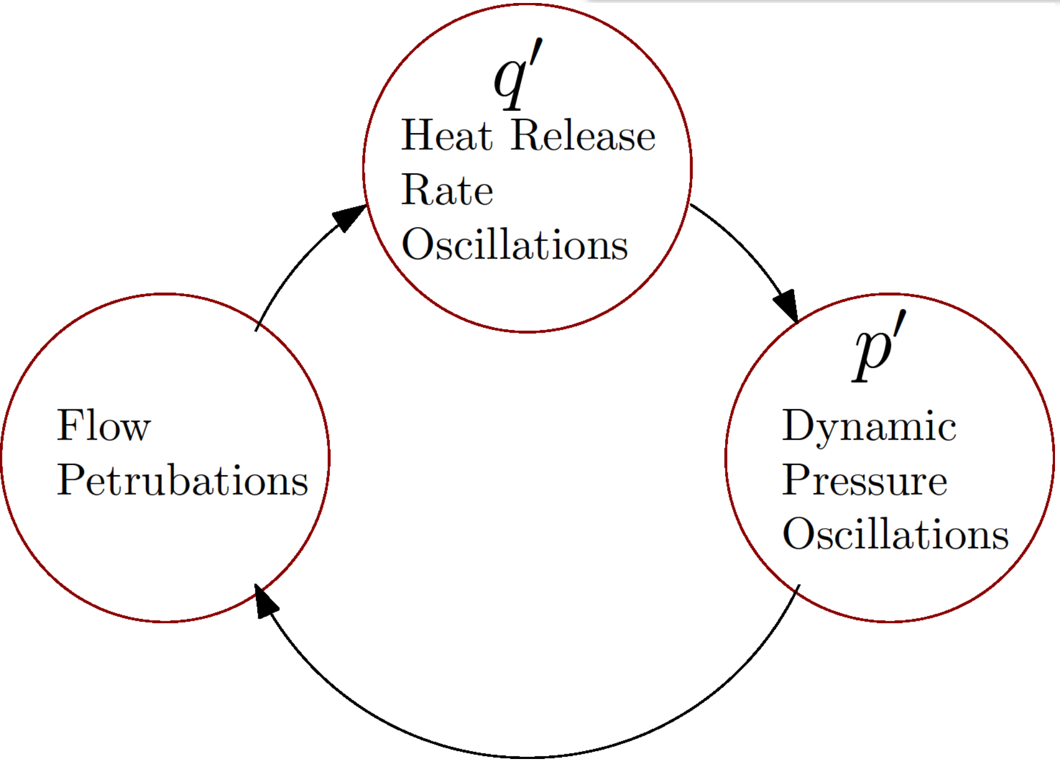
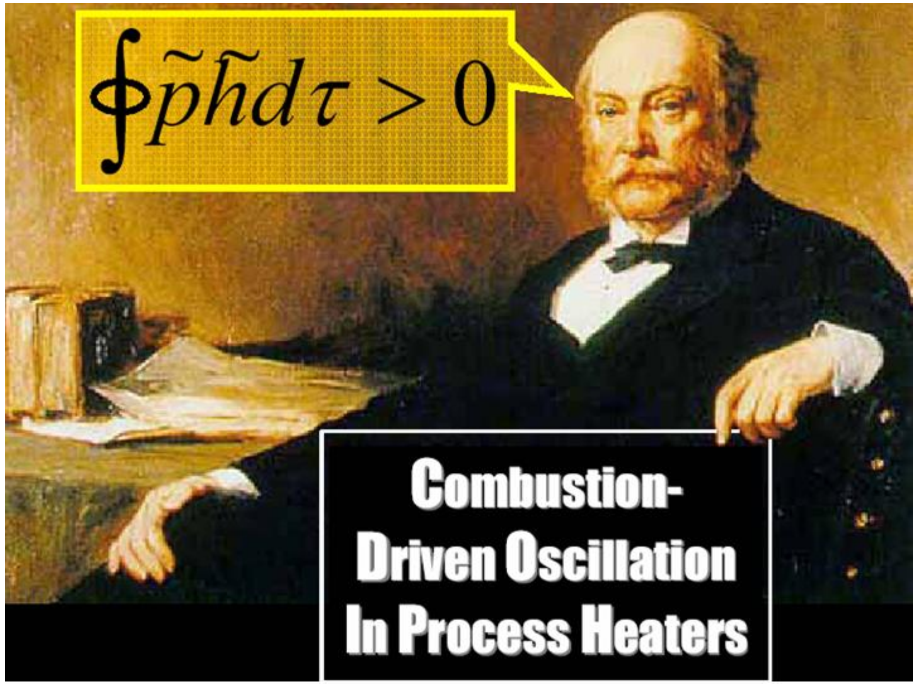
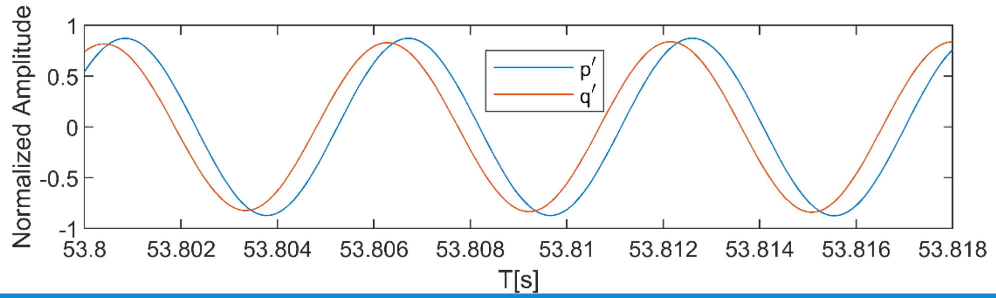
Thermoacoustic oscillations
Rayleigh Criterion







Rayleigh criterion: Perpetuation of thermoacoustic oscillations if p’ and q’ oscillate in phase

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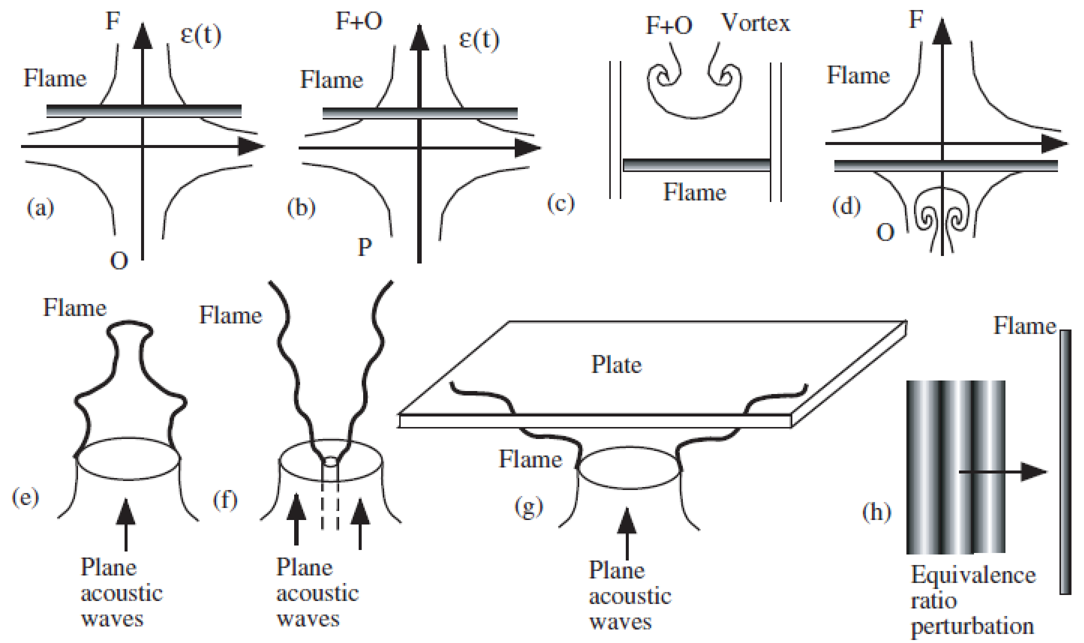
Thermoacoustic Oscillations
Perpetuation Mechanisms



Thermoacoustic mechanisms (right). Candel et al. 2002, Proceedings of the Combustion Institute

- Perpetuation mechanisms are still under investigation but in essence are described by the Rayleigh criterion.
- Mechanisms in elementary combustors include: Vortex-Flame interactions, Equivalence ratio oscillations, Oscillatory Flame Stretching and others.
- Still the understanding of the perpetuation mechanisms in complex systems are not fully understood. Further investigation is required.

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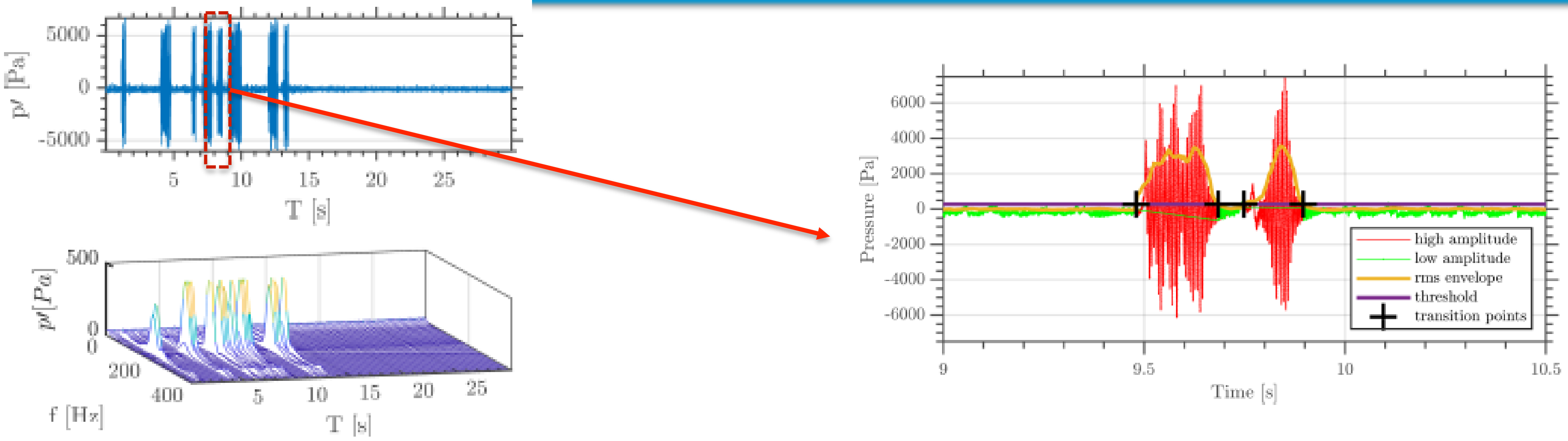
Thermoacoustic Oscillations
Triggering Mechanisms



- The Rayleigh criterion does not examine what causes the combustor to become thermoacoustically unstable in the first place.
- The physics of the triggering mechanisms are even less well understood.
- It is important that these mechanisms are investigated because transitions to instabilities happen abruptly, with no prior forewarning: Subcritical Hopf Bifurcations.

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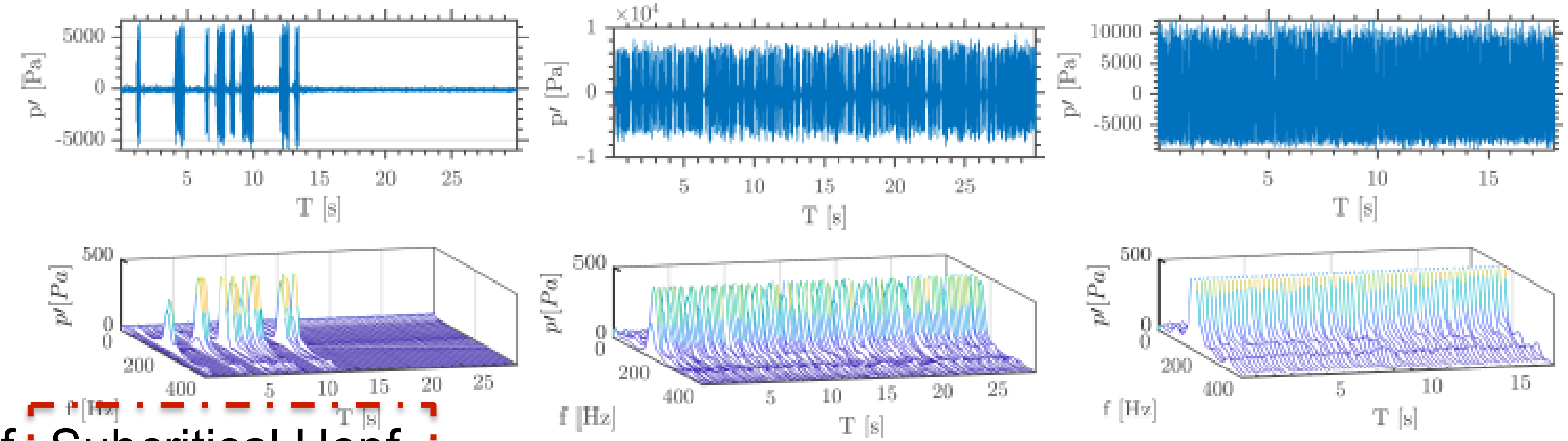
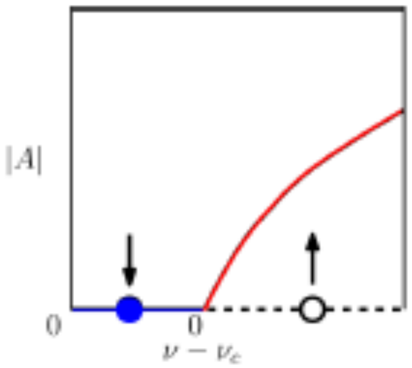
Thermoacoustic Oscillations
Triggering Mechanisms-Useful Concepts

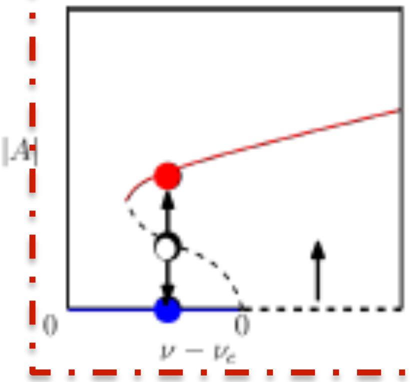
Bifurcation parameters: Increasing any of φ, χ_{H2} , $T_{preheat}$ etc. probability of triggering increases



Supercritical Hopf



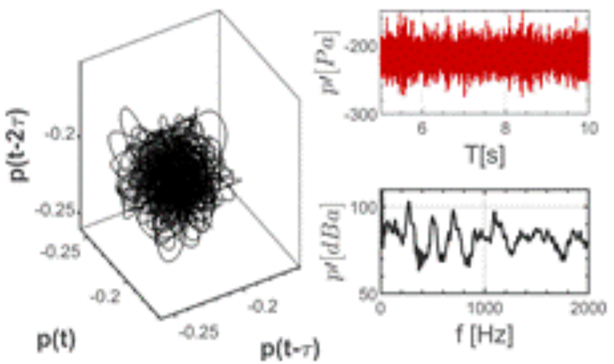
Subcritical Hopf



Bistability: Intermittent transition from broadband low amplitude dynamics to deterministic oscillations.

Thermoacoustic Oscillations
Nonlinear dynamics representation

Quiescence



Dynamic Pressure

Fourier Spectra

Dynamics: Attracted to fixed point and demonstrate stochastic low amplitude pressure fluctuations.

- Triggering occurs upon increasing a bifurcation parameter such as the equivalence ratio, the preheat temperature, the hydrogen content etc.

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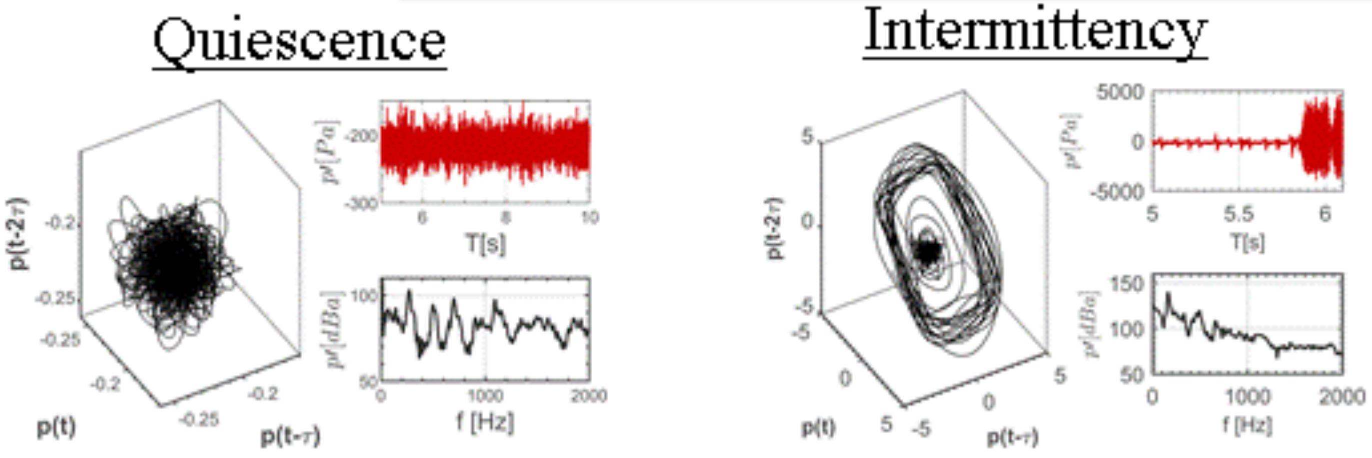
Thermoacoustic Oscillations
Nonlinear dynamics representation



<u>Dynamics:</u> Toroidal transition between limit cycle and fixed point. Emergence of coherent dynamics amidst a quiescent background.

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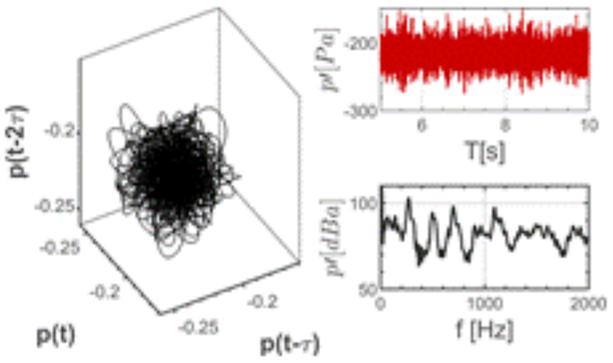
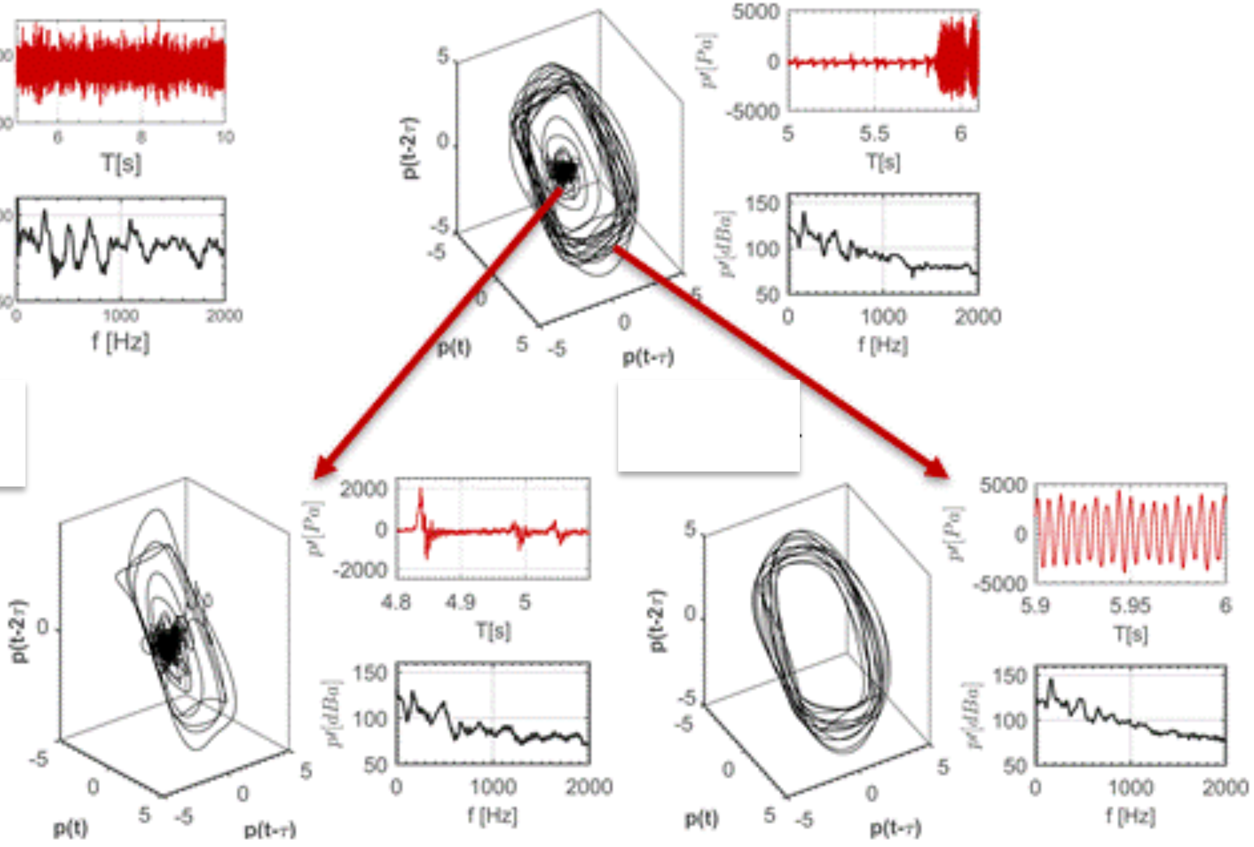
Thermoacoustic Oscillations
Nonlinear dynamics representation

Quiescence



Intermittency



Dynamics: Fixed point and toroidal transition

Dynamics: Limit cycle

Thermoacoustic Oscillations
Nonlinear dynamics representation

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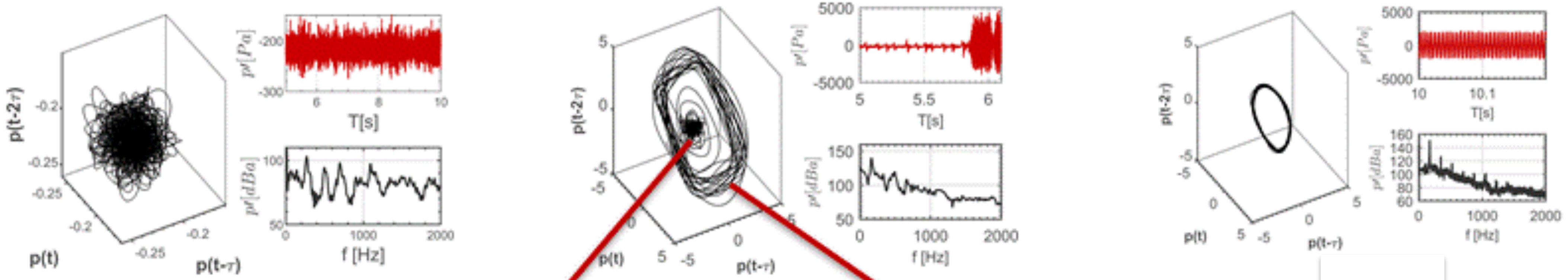
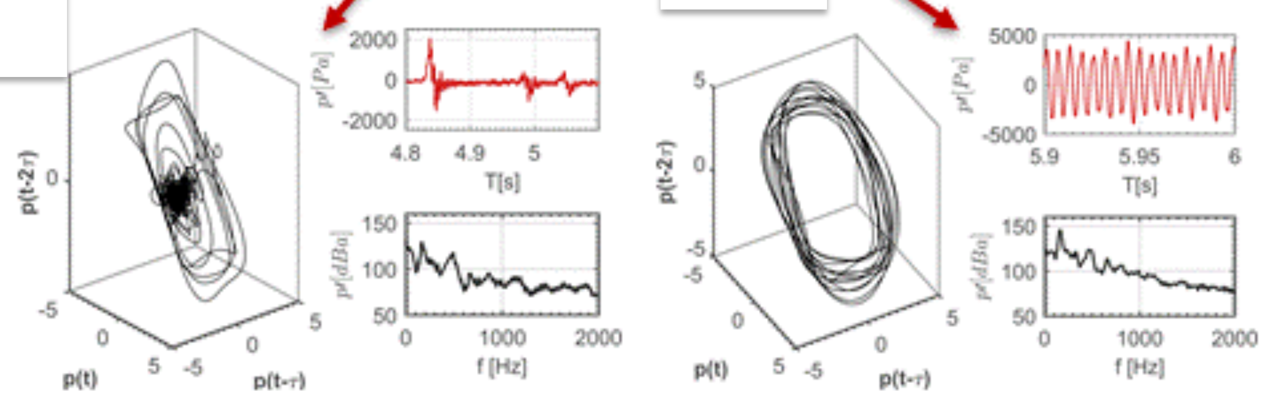
Quiescence

Intermittency

Limit Cycle



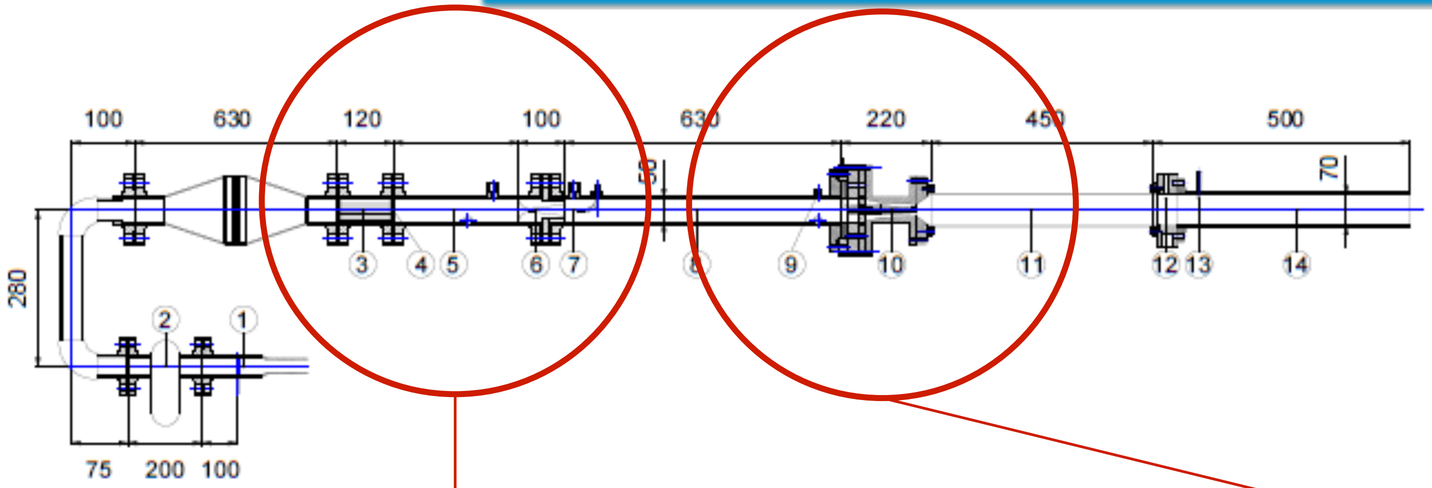


Dynamics:
Consistent attraction to limit cycle.

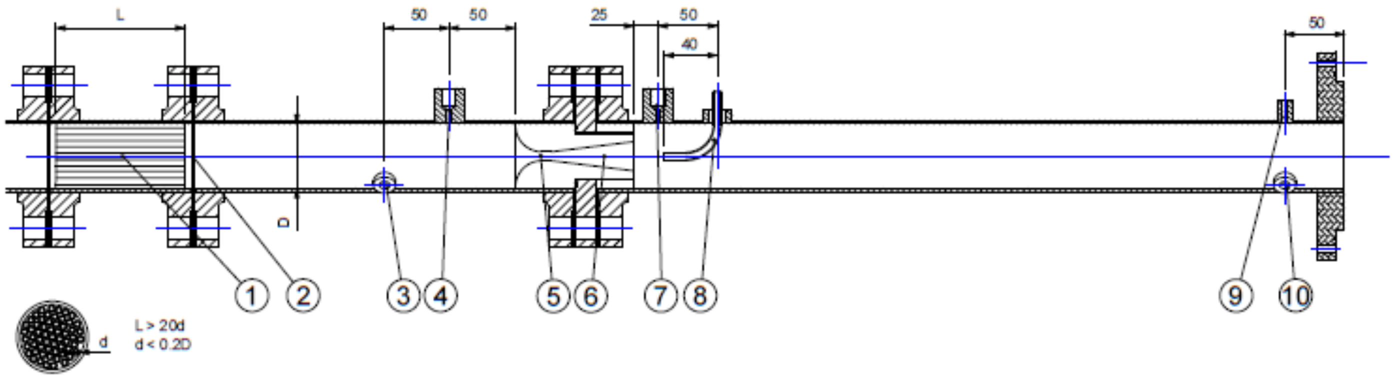
Research Aims

- Increase understanding of physical mechanisms causing the triggering of thermoacoustic instabilities.
- Increase understanding of physical mechanism causing the perpetuation of combustion instabilities.
- Understand how fuel consistency and chemistry affect these mechanisms.

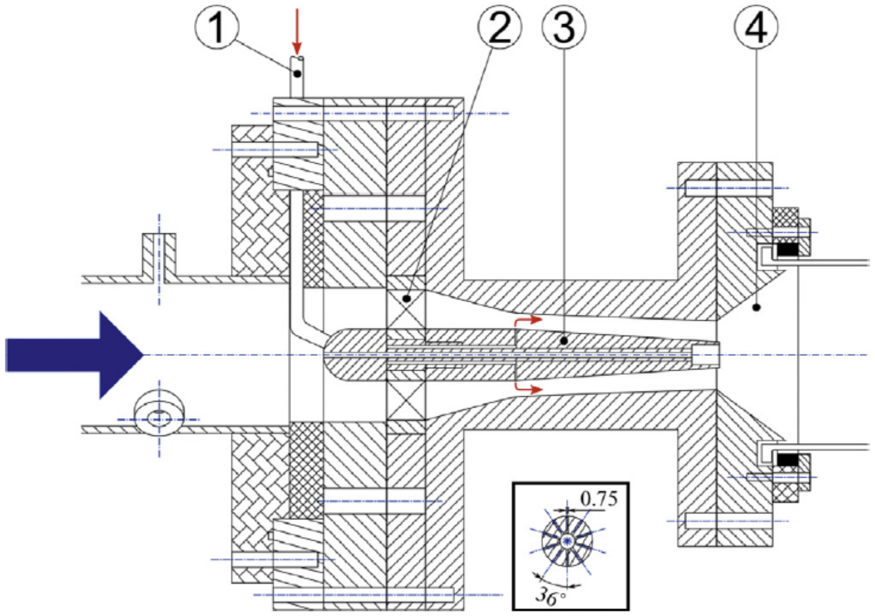
Experimental Configuration
Boundary Conditions



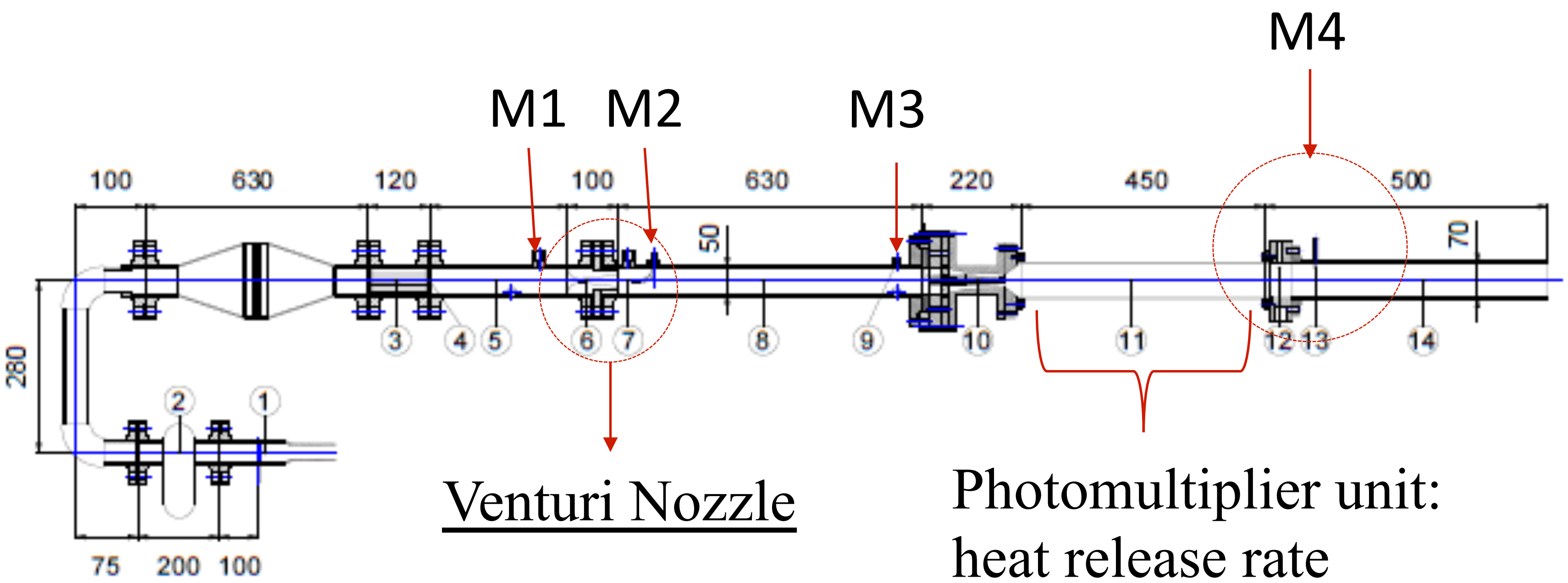
Venturi Nozzle: Chocked Air Flow



Burner: Chocked Fuel Injection



Experimental Configuration
Measurement of fundamental quantities



Venturi Nozzle

Photomultiplier unit: heat release rate (CH^*, C_2^*, OH^*)

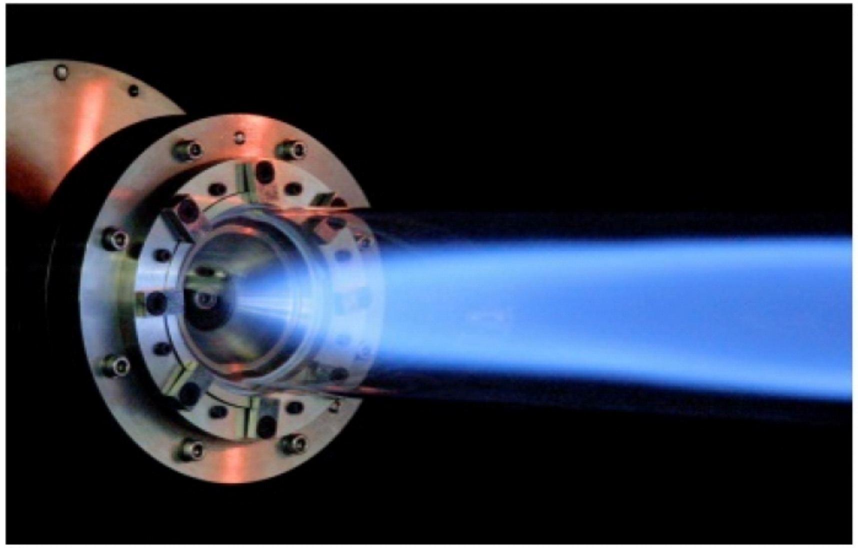
M1, M2: Monitor pressure drop across Venturi nozzle.

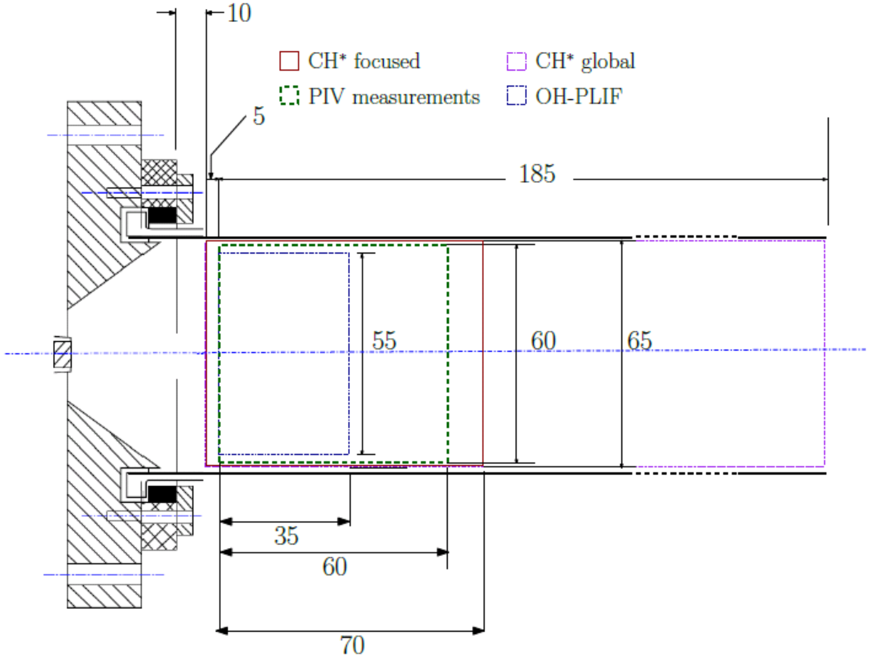
M2, M3: Acoustic wave amplitude inside duct (2-mic method)

M4: Standing wave along combustor

M5 (not shown): Pressure in fuel supply line

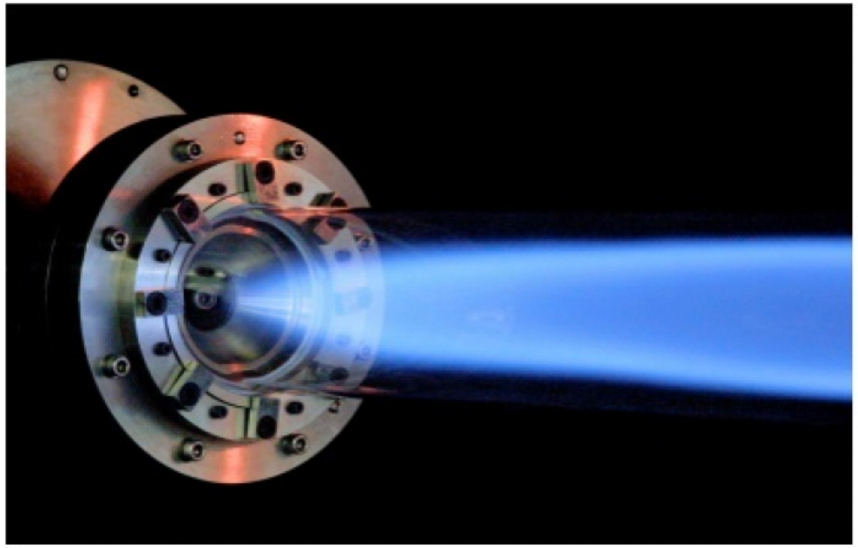
Experimental Configuration
Swirler and Optically Accessible Combustion Window

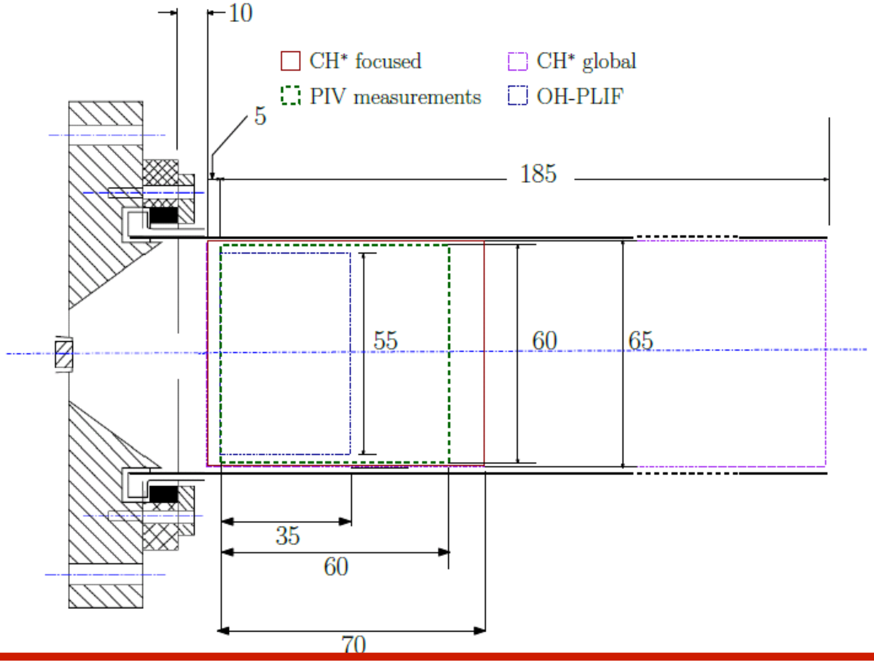




Measurement techniques: High speed CH* imaging (3000 Hz), High speed PIV (3000 Hz), OH-LIF (phase conditioned with acoustics), dynamic pressure, PMT integral heat release rate

Experimental Configuration
Swirler and Optically Accessible Combustion Window





- Geometry remarkable characteristics:
  1. Highly confined nature of the combustor.
  2. The flame is susceptible to touching the combustor walls.
  3. Diffuser prevents the formation of outer recirculation zones.

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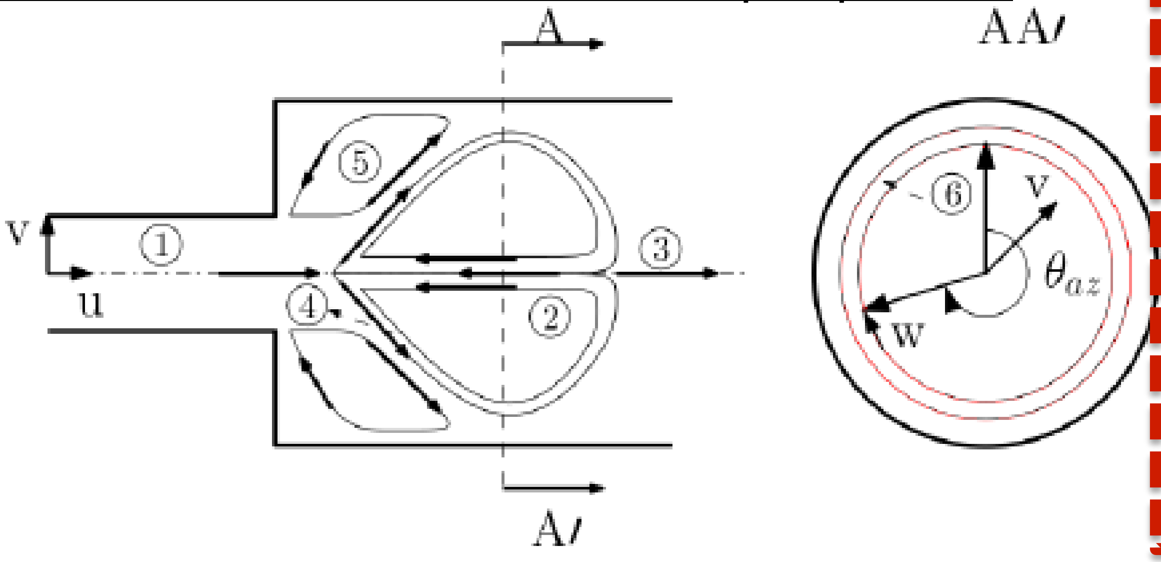
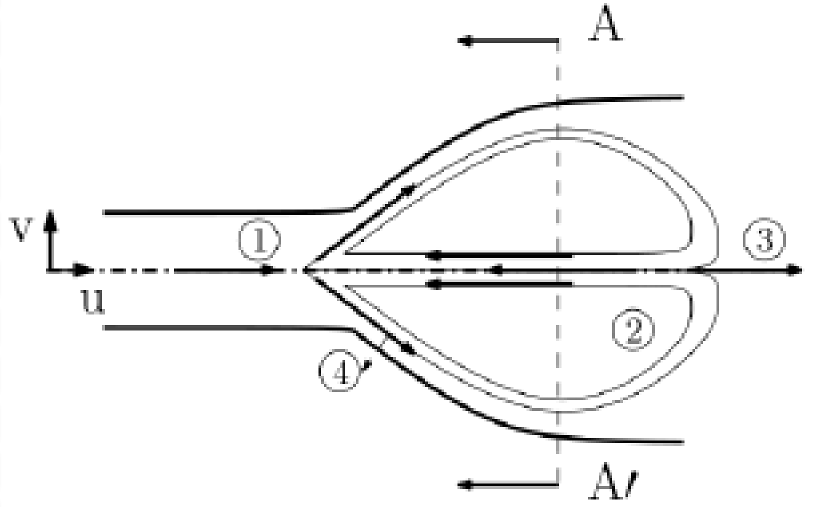
Experimental Configuration

Typical Swirling Flowfield Structure

Flow field structure with sudden-step expansion



Flow field structure with diffuser at the inlet



- 1. Upstream flow, 2. Inner Recirculation Zone, 3. Downstream flow, 4. Shear Layers, 5. Outer Recirculation Zone.

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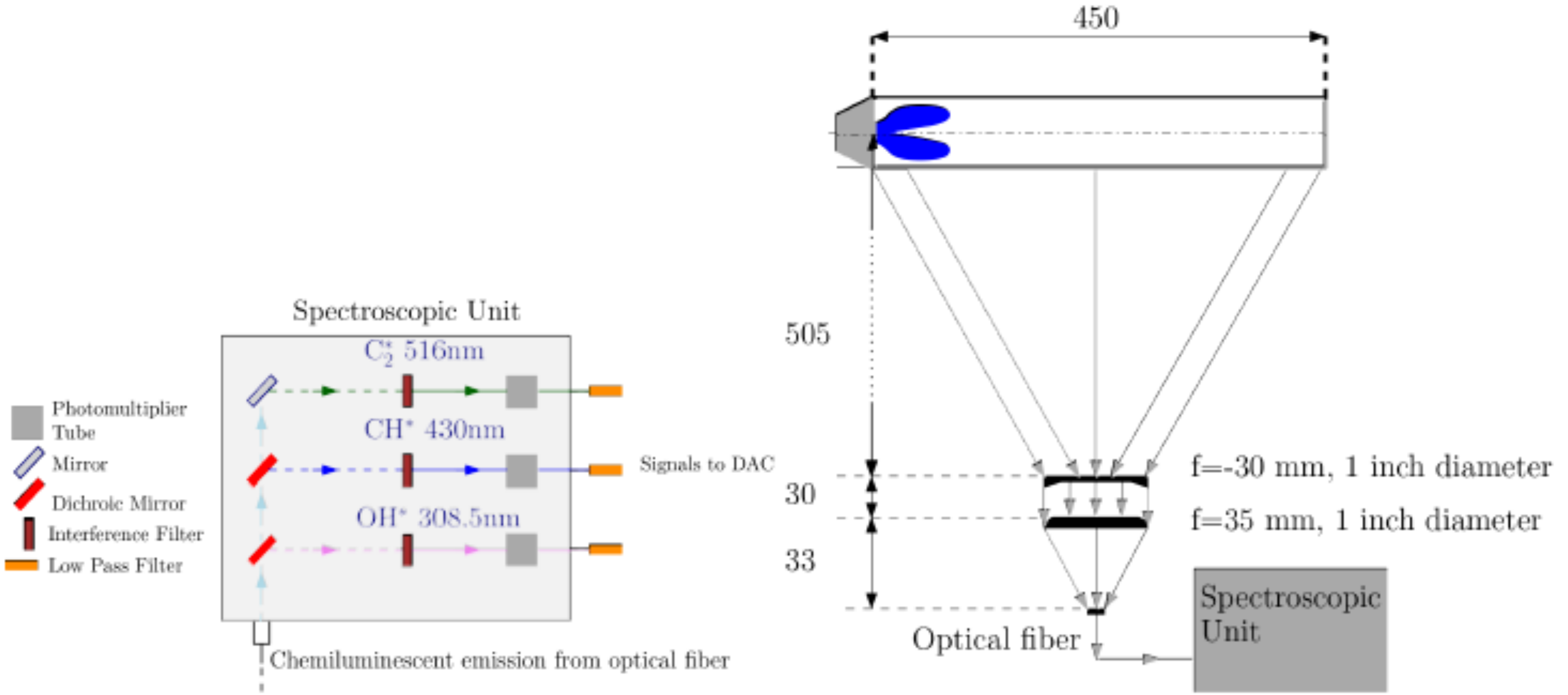
Experimental Configuration

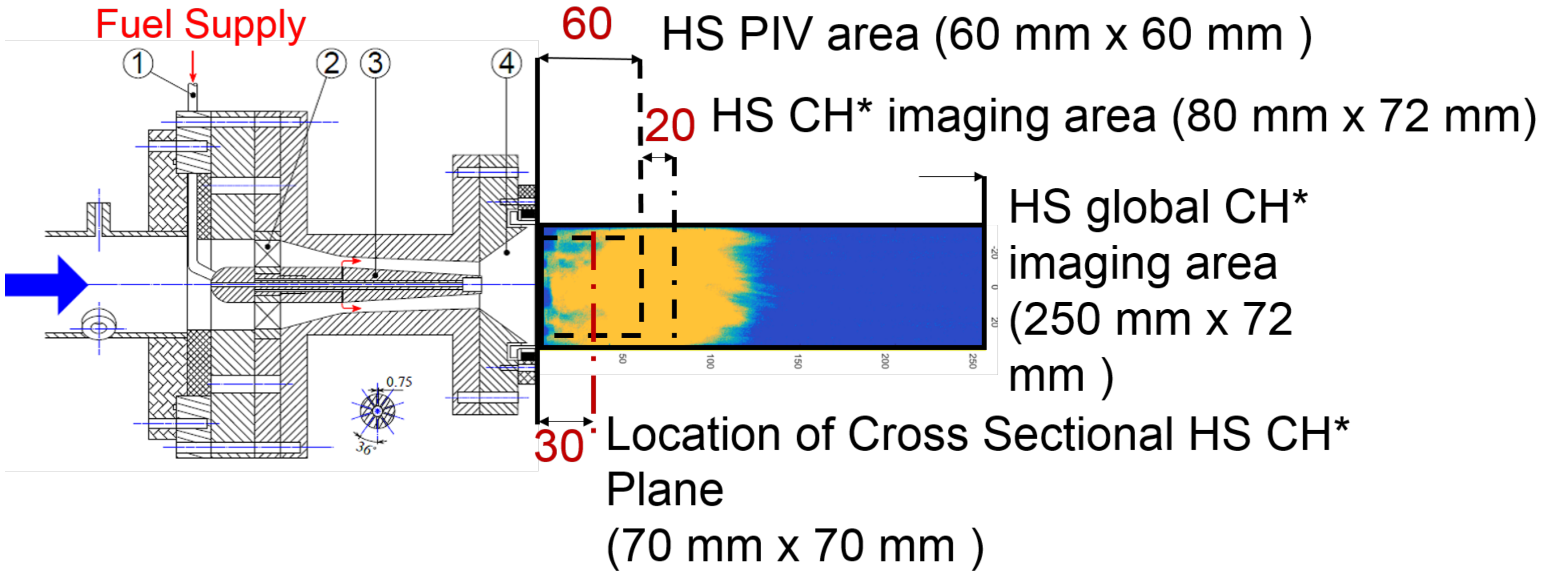
Photomultiplier Tube (PMT) for Chemiluminescent Intensity: Proxy of Global Heat Release



- The integral heat release rate is monitored by the chemiluminescent intensity of species OH^*,CH^*, C_2^*

Experimental Configuration

High speed imaging of Chemiluminescent Intensity: Proxy of Heat Release distribution



- The <u>spatial distribution</u> of heat release rate is monitored by the High Speed imaging of the chemiluminescent intensity distribution of species OH^* or CH^*

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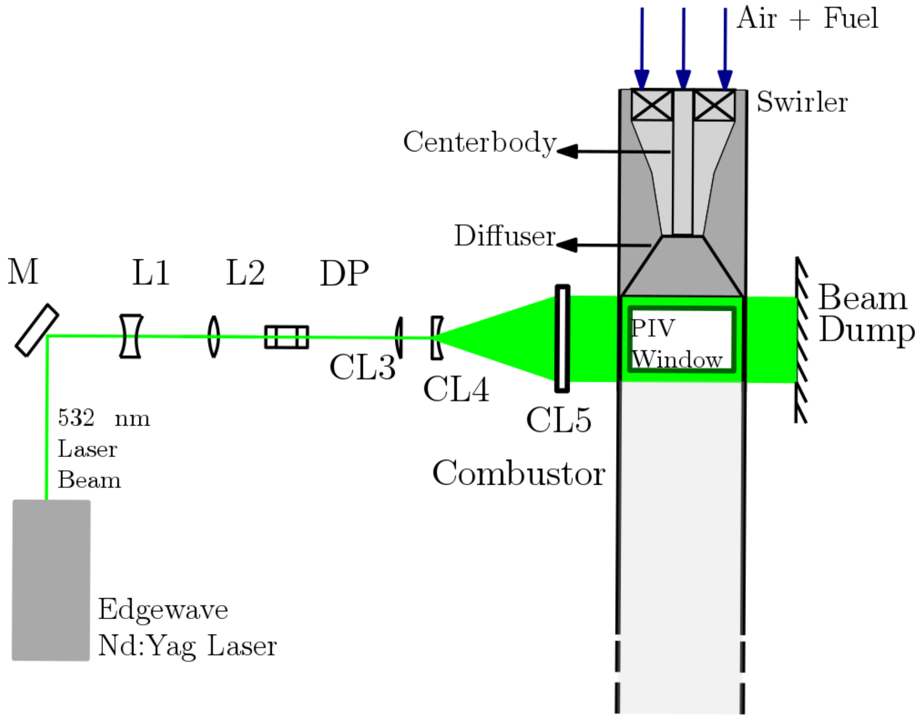
Experimental Configuration

Particle Image Velocimetry Measurements-Challenges of implementation

PIV Optical Configuration



- PIV is an optical diagnostic technique wherein a flow seeded with a heat resistive powder is twice illuminated. The successive images (with a dt of a few ~ μs) yield the velocity field on the illumination plane.
- Challenges:
  - ➢ Deposition of particles on combustor walls, limits time window to acquire measurements.
  - ➢ Proximity of combustor walls with the flame precipitates deposition of particles.
  - ➢ Due to the above, it is very difficult to capture transitions into Subcritical Hopf Bifurcations.

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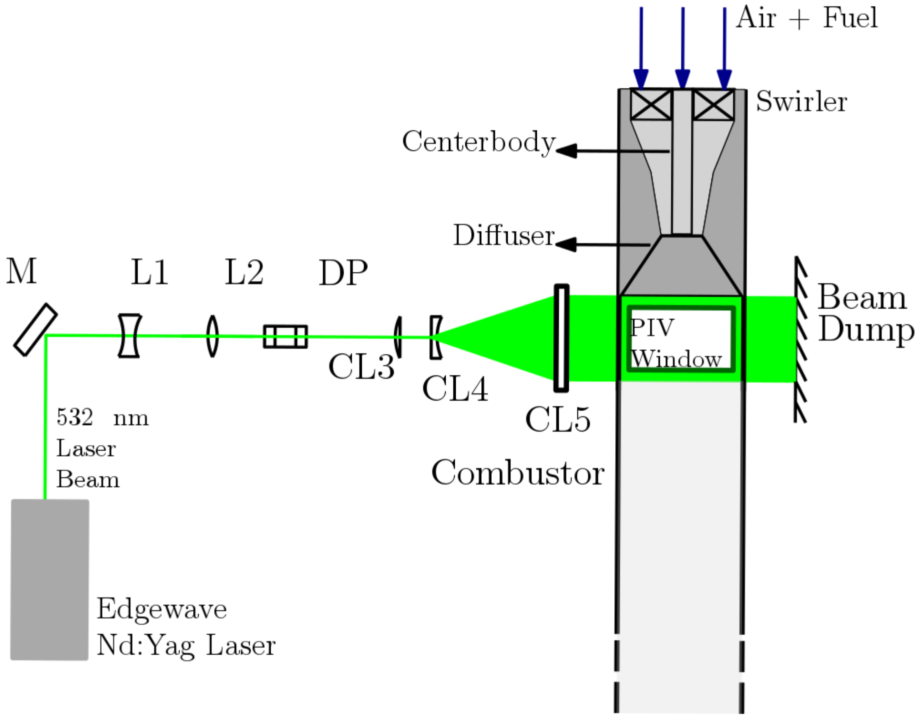
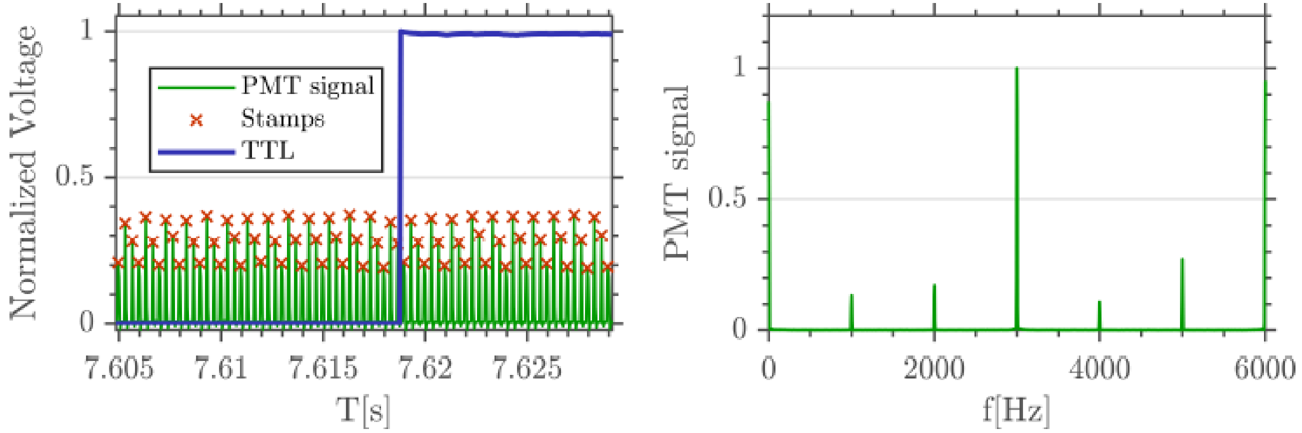
Experimental Configuration
Particle Image Velocimetry Measurements-Details of implementation

PIV Optical Configuration



PIV Synchronisation Signal



dt=4µs, 3000 Hz, FOV: 60 mm x 60 mm, Interrogation windows 16 x 16 pixels, 75% overlap, Resolution: 0.23 mm, Nominal uncertainty: 0.06 m/s.

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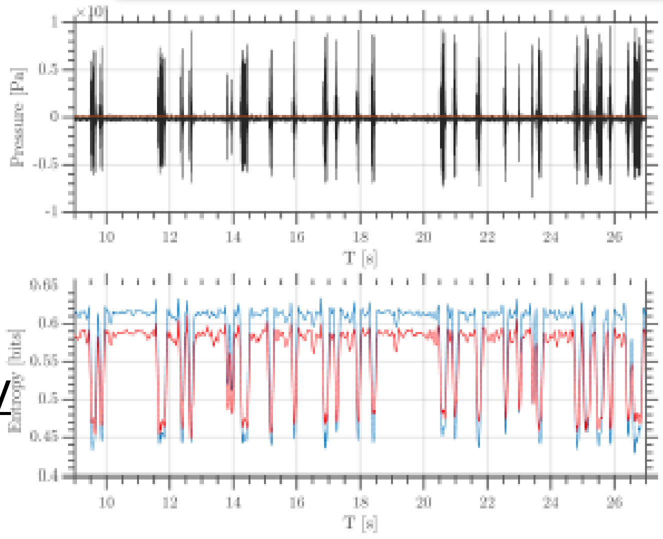
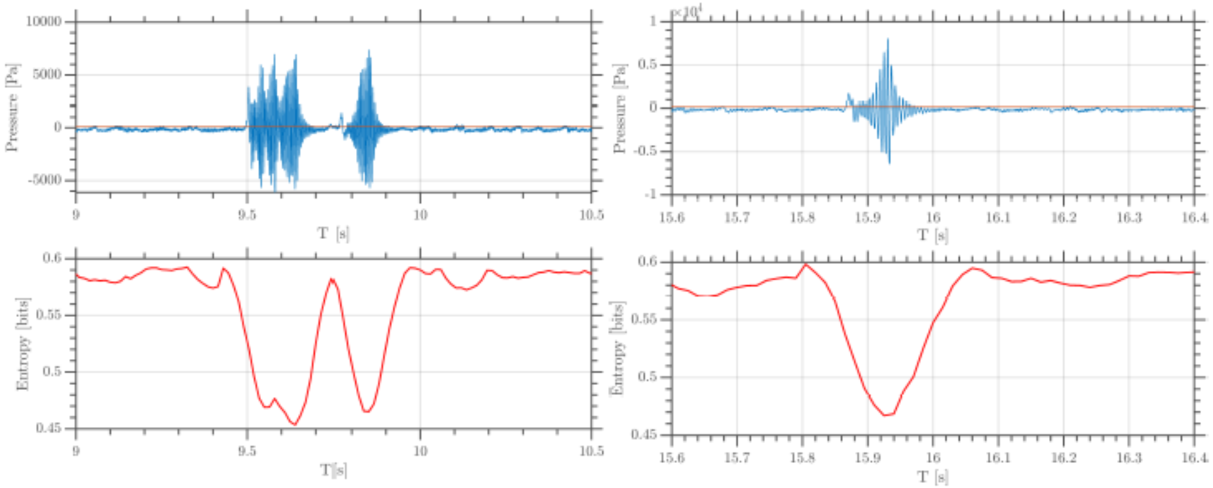
Experimental Configuration

Short Term Prediction Signals ahead of Pending Transition-Permutation Entropy

Dynamic Pressure

Permutation Entropy

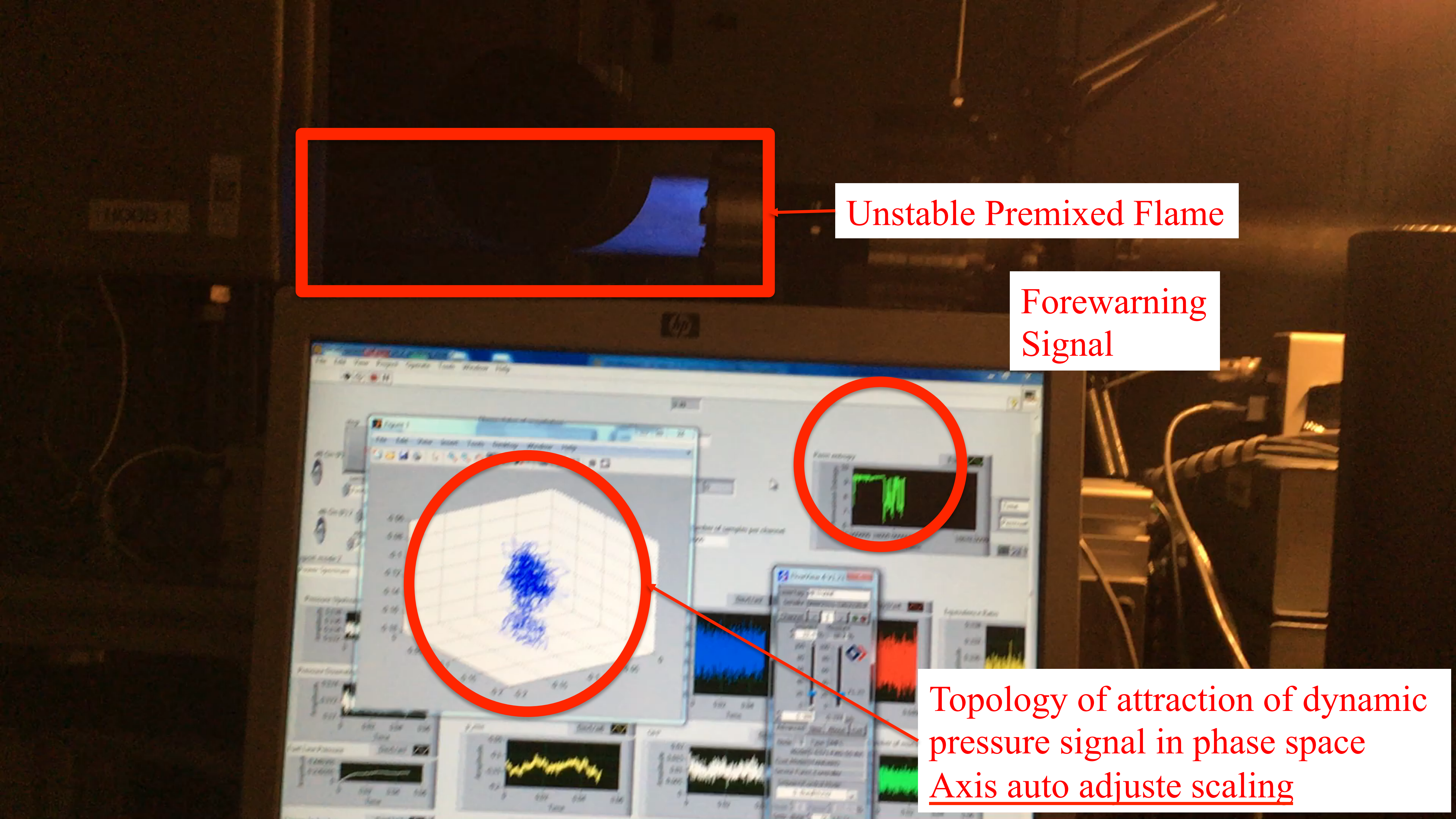




(a) T=[9 s-10.5 s]

(b) T=[15.6 s-16.4 s]

- Since transition into thermoacoustic instability is accompanied with loss of randomness and emergence of periodicity, a short term prediction algorithm is required to quantify this transition.
- The permutation entropy was implemented online in order to trigger the PIV diagnostics and capture the transition into thermoacoustic instability, thus avoiding 'seeding' particle deposition problems during acquisition.
- The permutation entropy is a measure of the complexity of the time series. A higher number of possible permutations corresponds to a stochastic aperiodic state.


Unstable Premixed Flame
Forewarning Signal
Topology of attraction of dynamic pressure signal in phase space
Axis auto adjuste scaling

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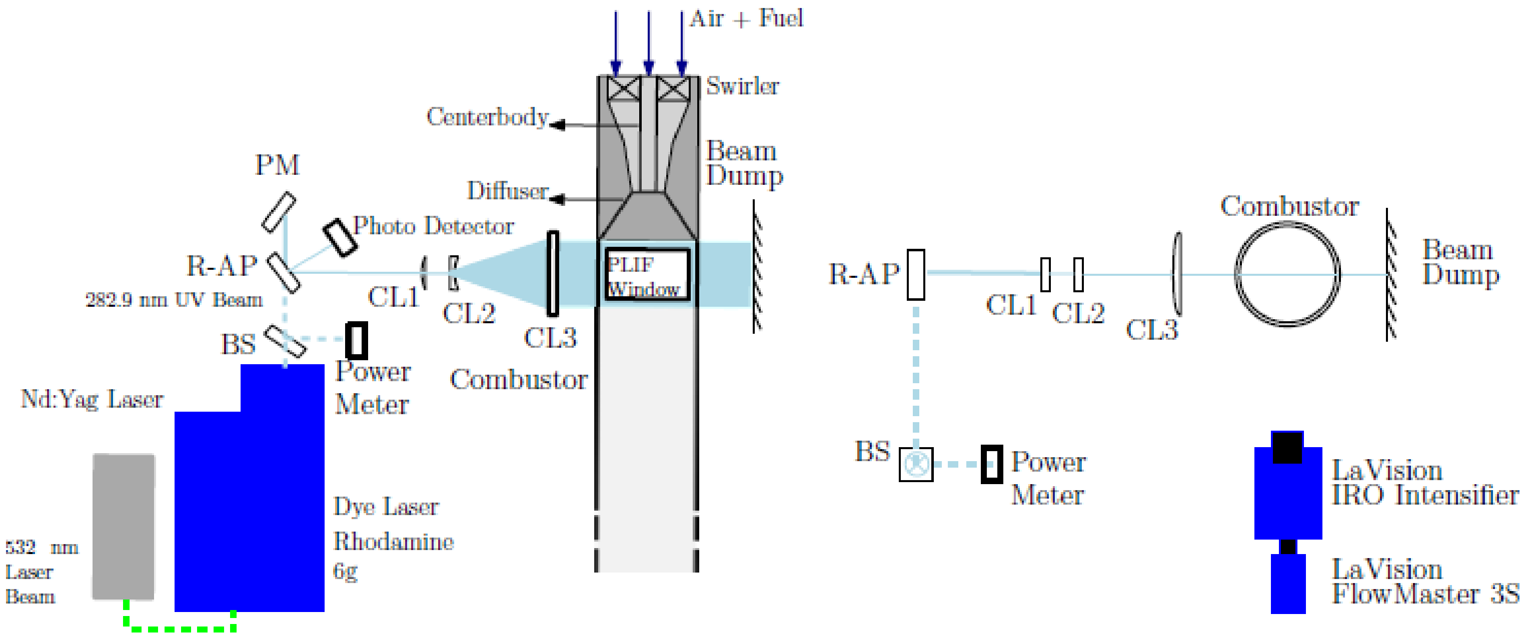
Experimental Configuration

OH-Planar Laser Induced Fluorescence (PLIF) Measurements

PLIF Optical Configuration



- PLIF is an optical diagnostic technique wherein an intermediate species of the flame is laser excited to an upper electronic state emitting a photon during de-excitation.
- The OH-PLIF species can be found in super-equilibrium concentrations along the flame front, hence it is easier to acquire better signal to noise ratio images.
- In the context of the current work, OH-PLIF is used to extract the flame front curvature statistics of the flame under quiescent, transitional, limit cycle states.

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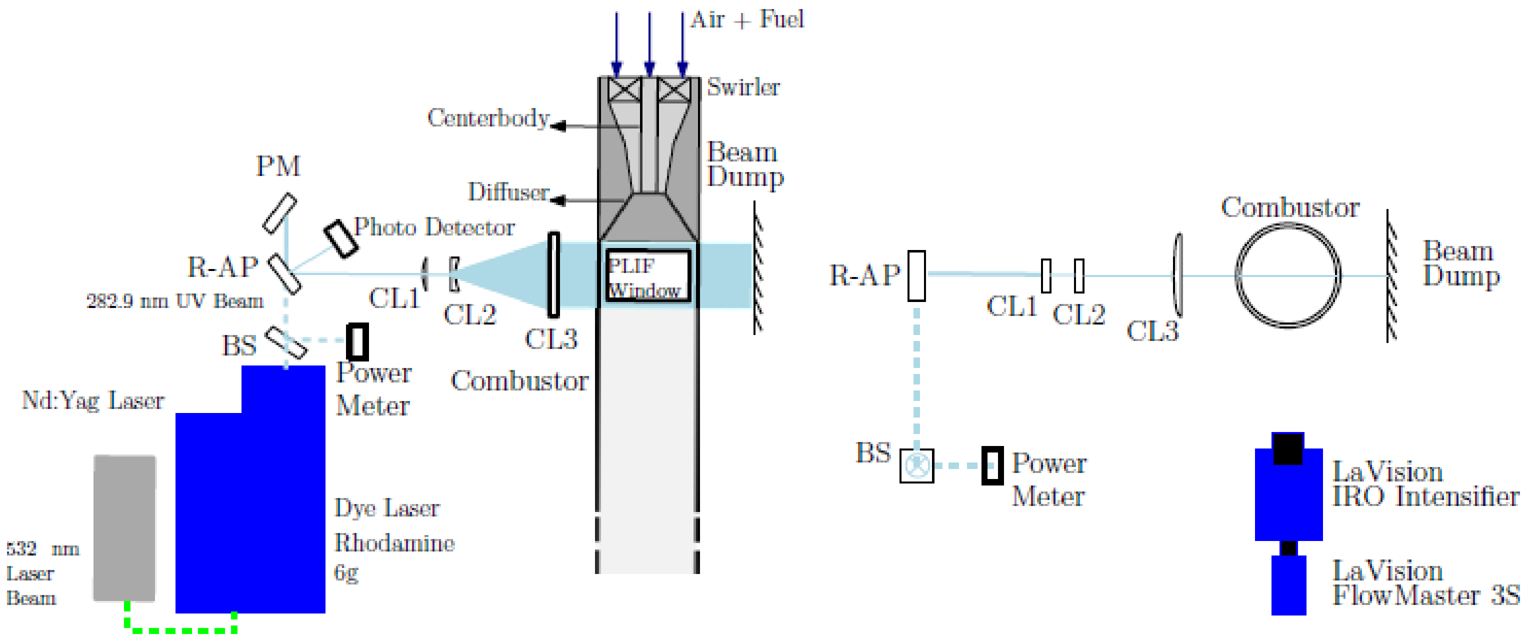
Experimental Configuration
Planar Laser Induced Fluorescence (PLIF) Measurements

PLIF Optical Configuration

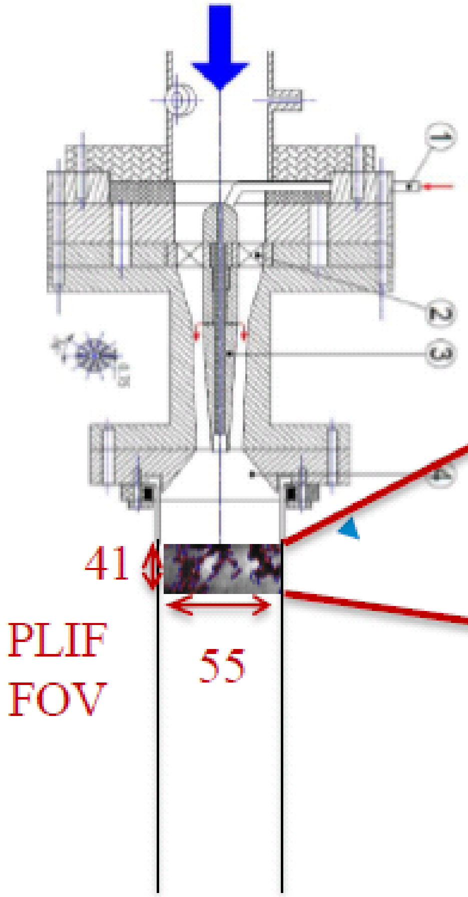


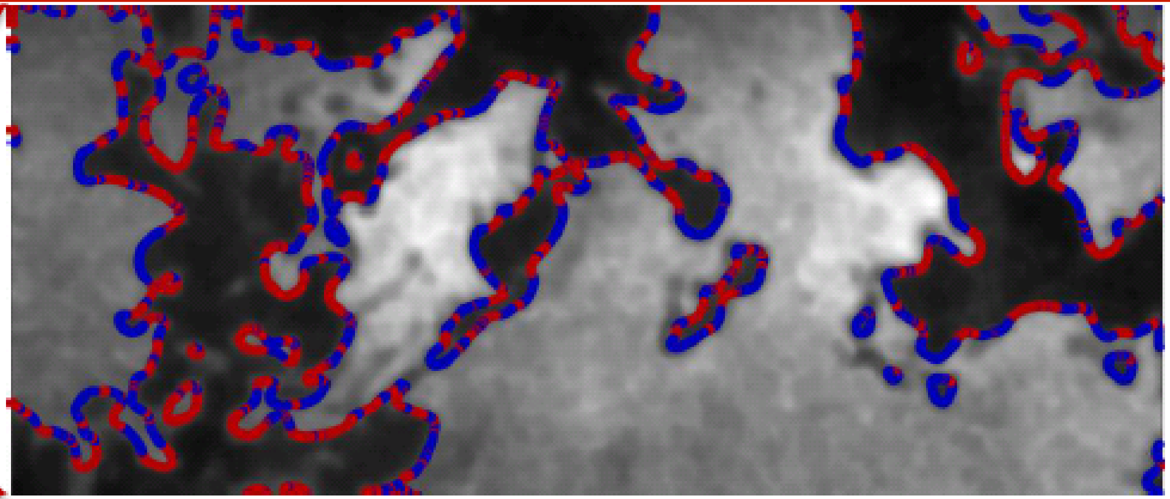
10 Hz, excitation $Q_1(6)$ transition line: $A^2\Sigma$-$X^2\Pi$ at 282.9 nm, light collected at 308 nm and 314 nm, dye laser output: 18mJ per pulse, field of view 35 mm x 35 mm, resolution of 5 line pairs / mm (curvature resolution)

Flame front curvature analysis

Flame front detection algorithm

Method: [Bayley et al., 2012] Bayley, A. E., Hardalupas, Y., & Taylor, A. M. (2012). Local curvature measurements of a lean, partially premixed swirl-stabilised flame. Experiments in Fluids, 52(4), 963–983.





Flow Direction

Burned | Unburned

Negative curvature

Burned | Unburned

Positive curvature

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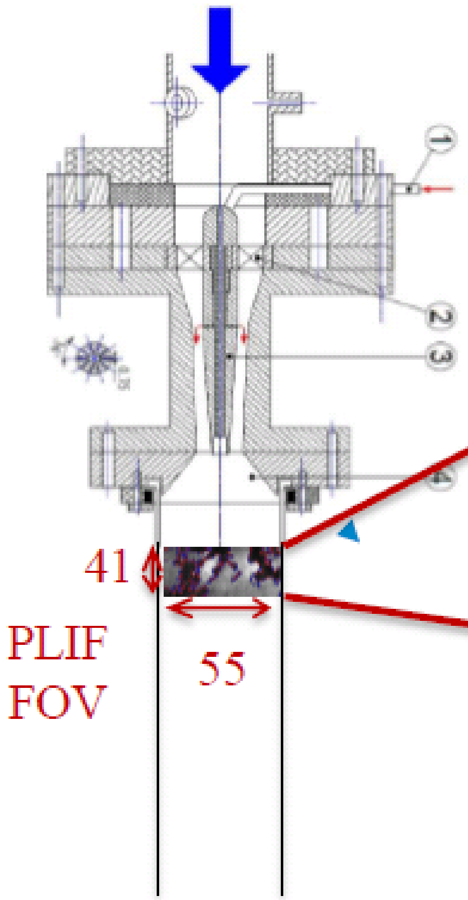
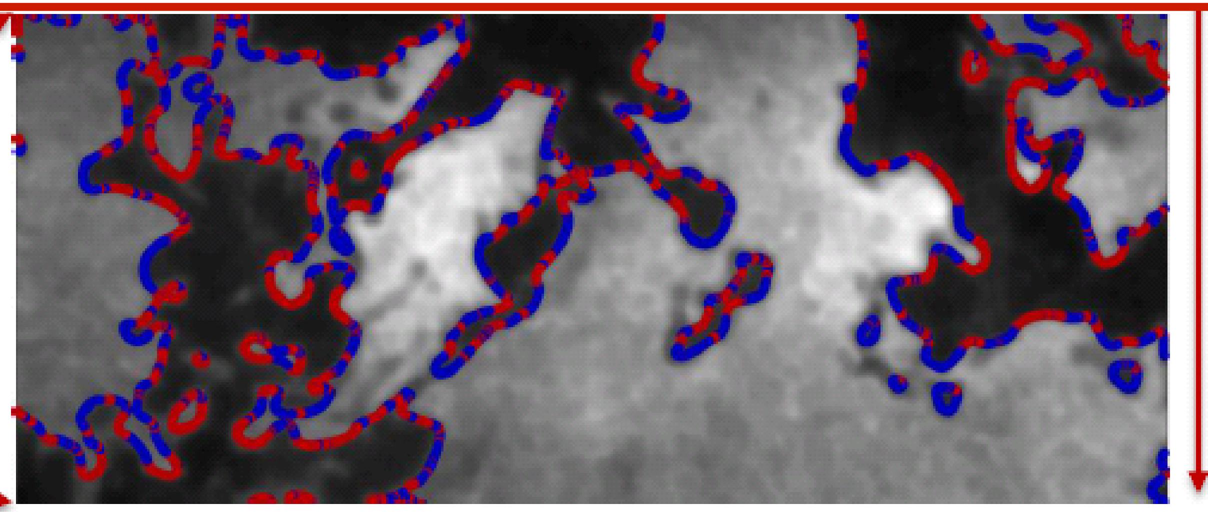
Flame front curvature analysis

Flame front detection algorithm

Method: [Bayley et al., 2012] Bayley, A. E., Hardalupas, Y., & Taylor, A. M. (2012). Local curvature measurements of a lean, partially premixed swirl-stabilised flame. Experiments in Fluids, 52(4), 963–983.





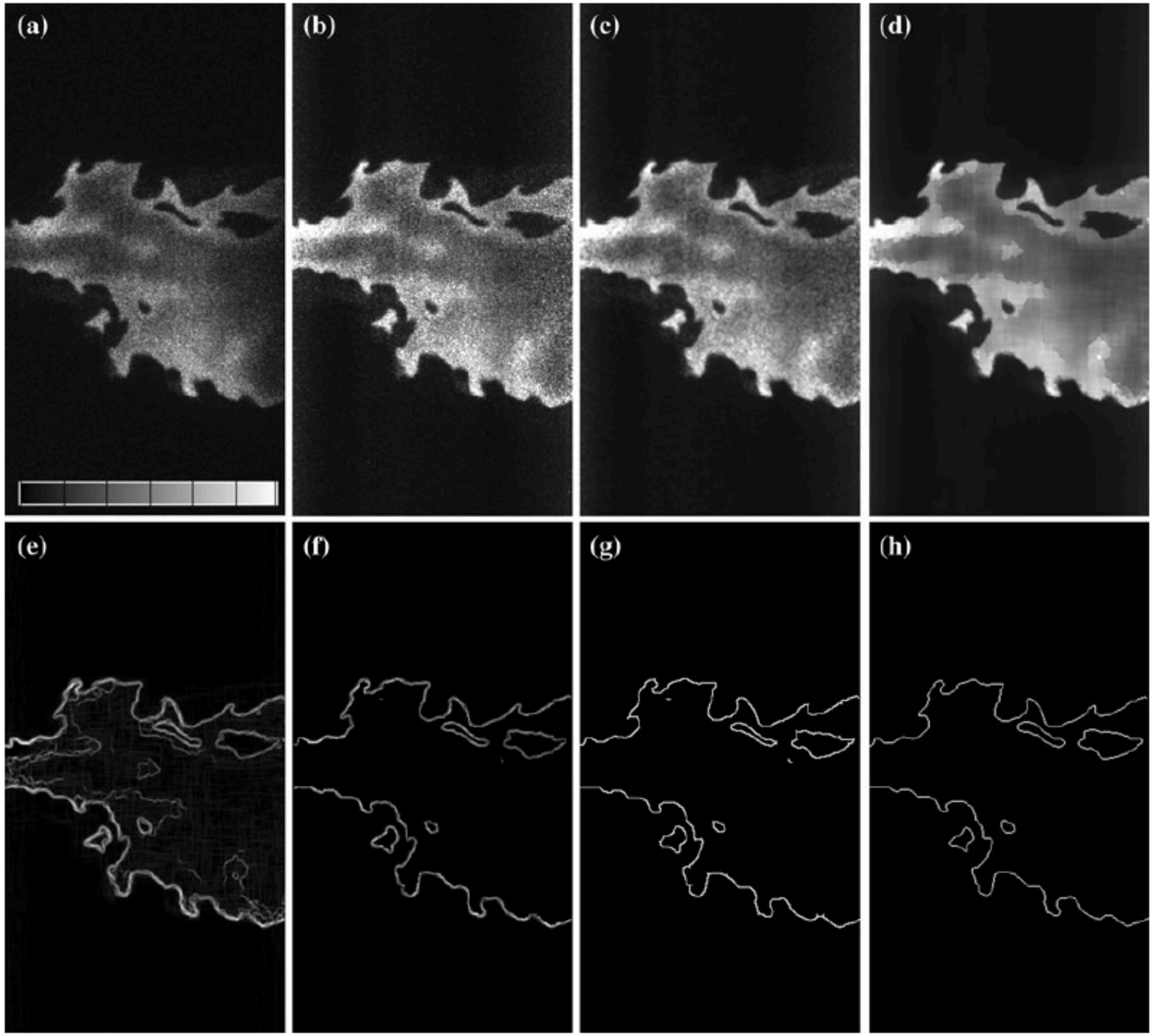
Flow Direction

Burned | Unburned

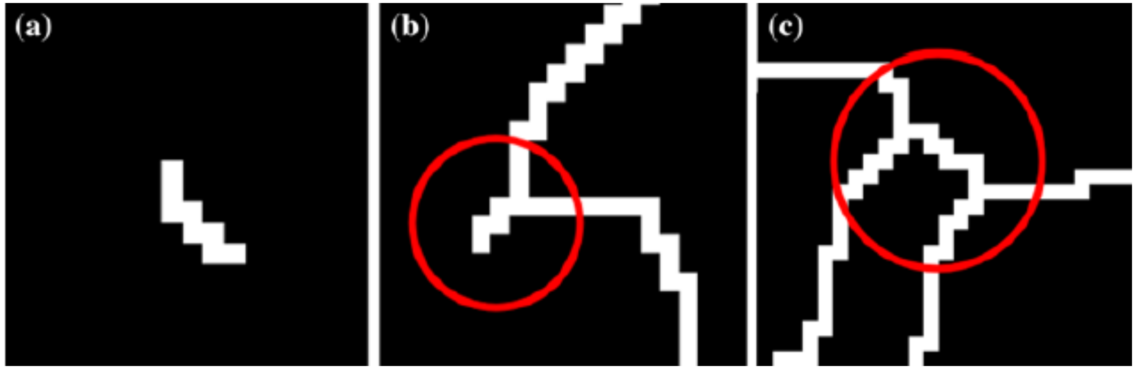
Negative curvature

Burned | Unburned

Positive curvature



Method avoids the erroneous cases as in the following examples and ensures that the flame curvature is measured accurately.



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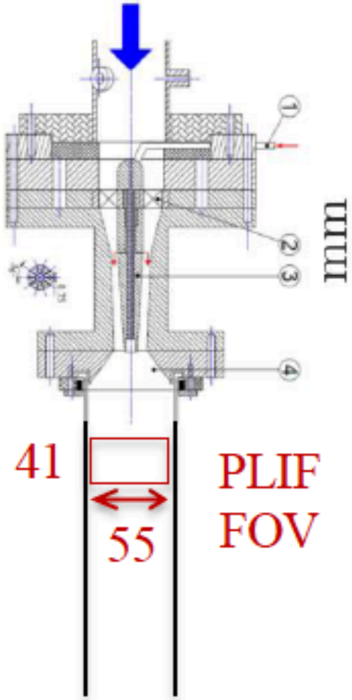
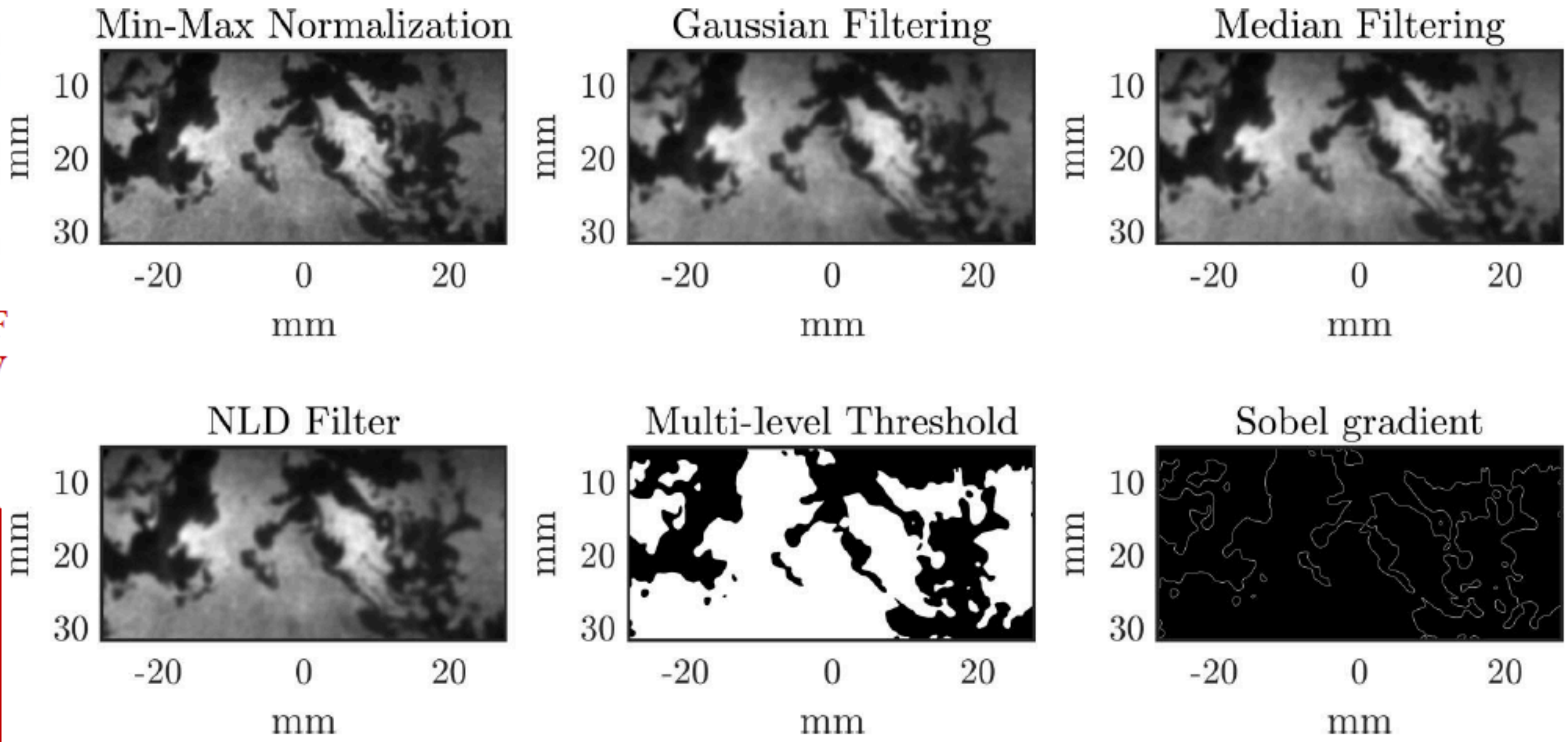
Flame front curvature analysis
Flame front detection algorithm



Resolution:
1376 x 1040
FOV: 55.135 mm x
41.659 mm
Resolvable curvature:
5 line pairs / mm

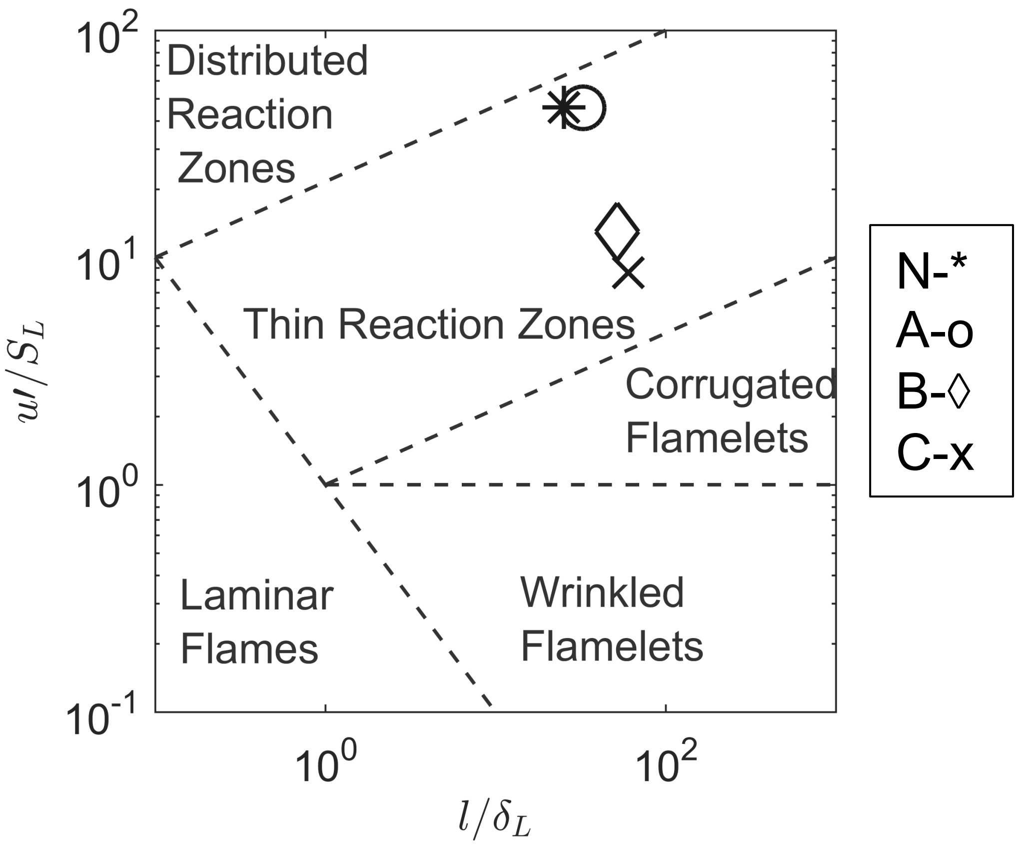


Period – 2 Limit Cycle

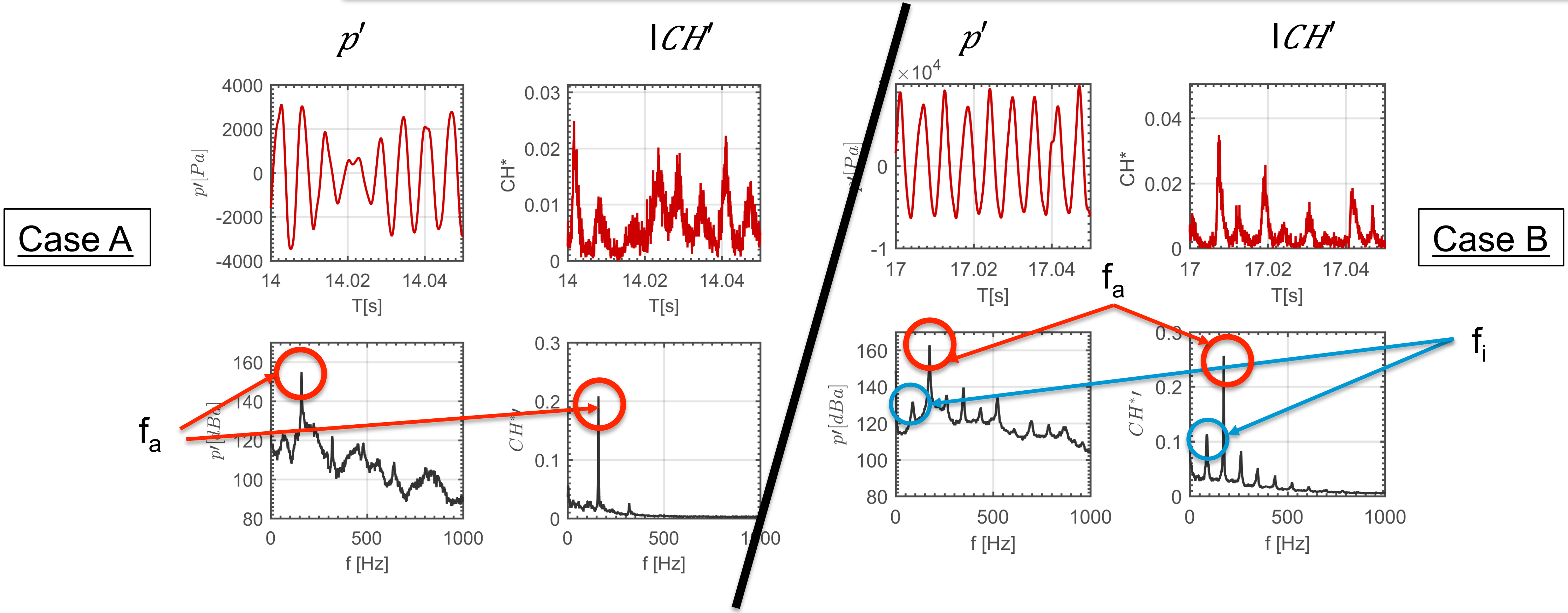
Operational Conditions

Premixed Combustion State with CH_4 fuel

Case ID	φ	Dynamic State	K_{ext} [1/s]
N	0.50	Intermittent	85
A	0.55	Period-1	236
B	0.60	Period-2	608
C	0.65	Period-2	1138



Manifestation of Period Doubling Bifurcation

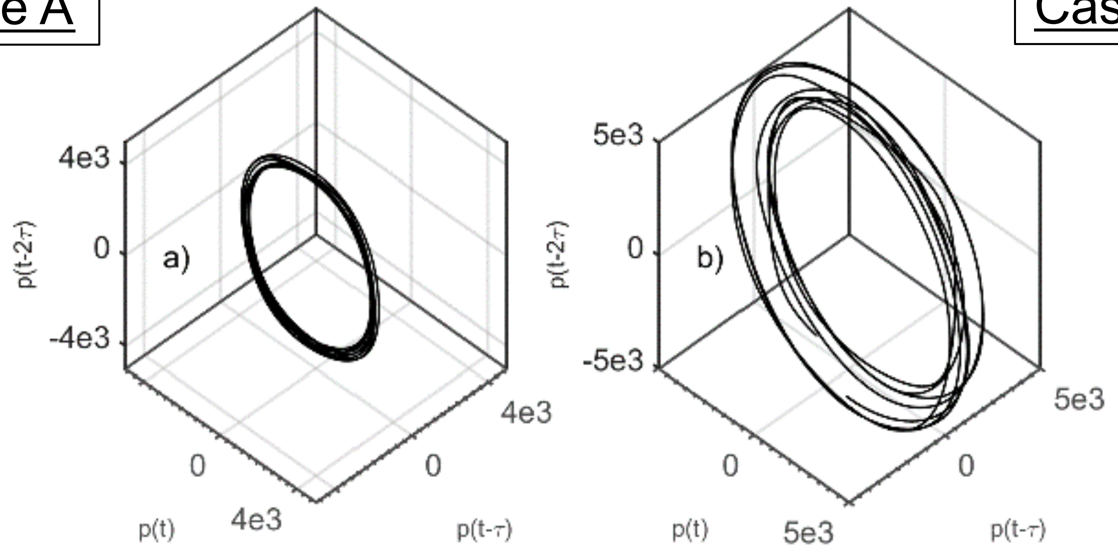


- On increasing φ under constant Re, the dynamics are attracted from a Period-1 limit cycle to a Period-2 limit cycle.

Manifestation of Period Doubling Bifurcation

Case A

Case B



Period 1 Limit Cycle

Period 2 Limit Cycle

➢ On increasing φ under constant Re, the dynamics are attracted from a Period-1 limit cycle to a Period-2 limit cycle.

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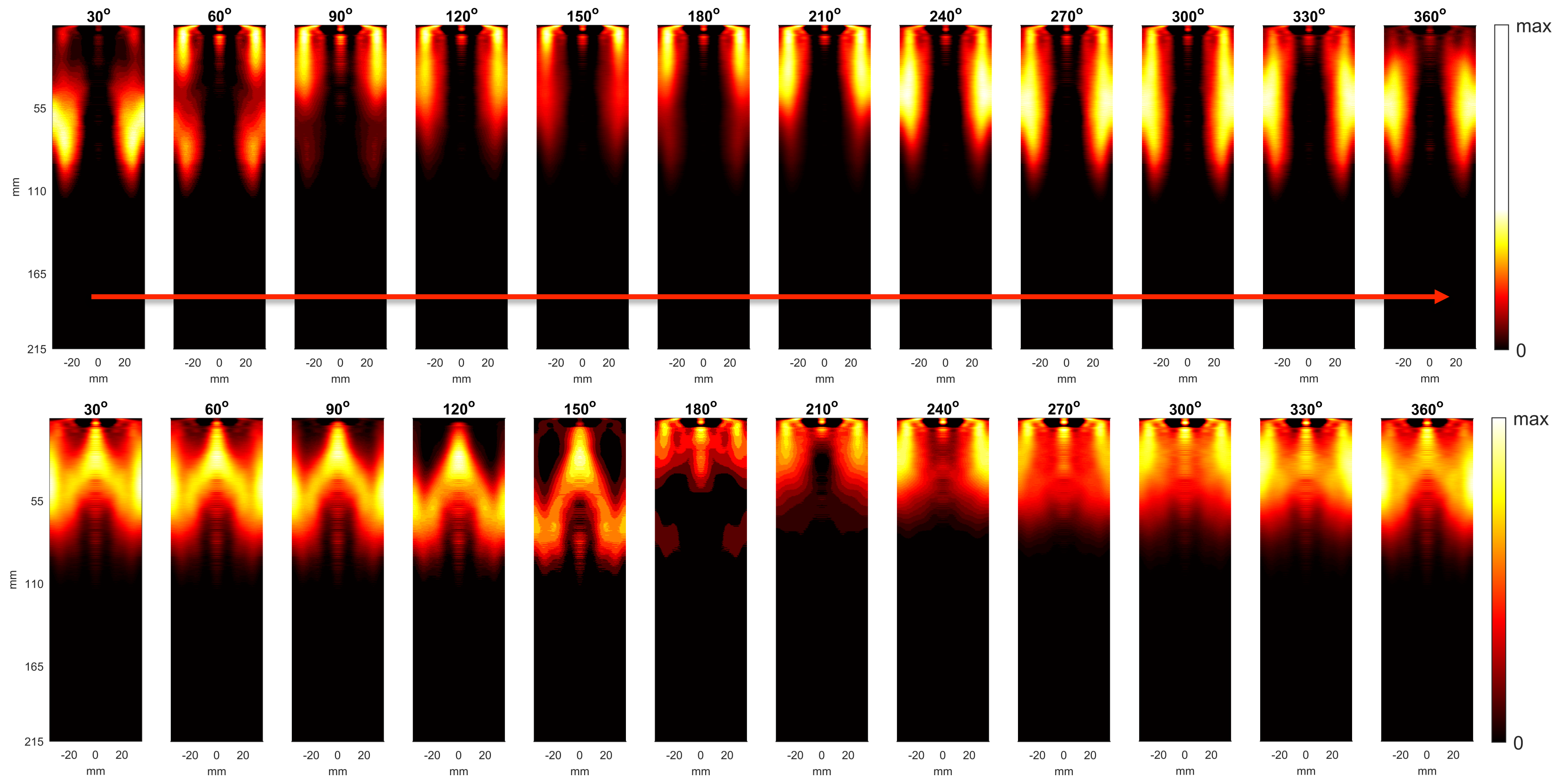
Manifestation of Period Doubling Bifurcation

Flame shape effects

Case A

Phase averaged structure

Case B



- ➢ The period 1 and period 2 flames assumes a V and M shape respectively.
- ➢ Phase averaged flame shape with respect to the fundamental frequency of instabilities.

DMD: Link between f_i and coherent sructures

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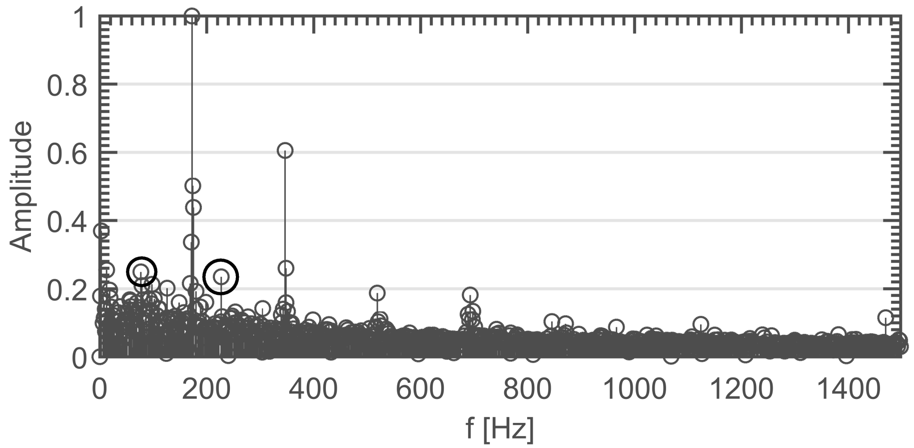
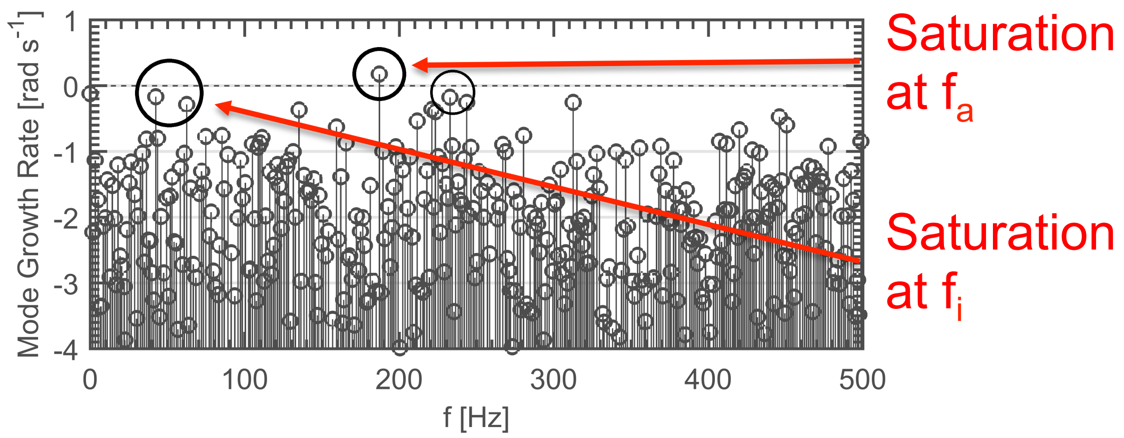
DMD Modes Amplitude



DMD Modes Growth Rate

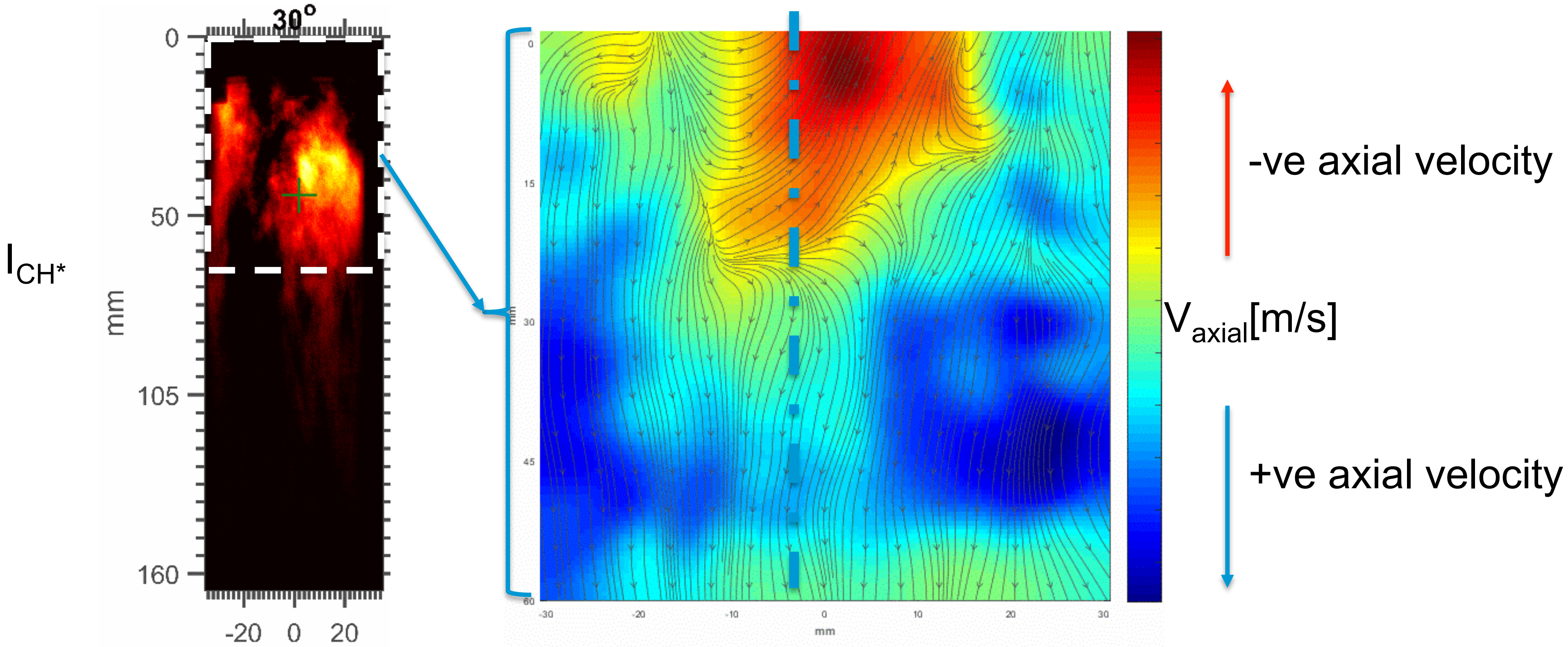


- Dynamic Mode Decomposition calculates <u>temporally orthogonal modes</u> to associate phenomena observed in *n* temporally equidistant snapshots $\{v_1, v_{2,\ldots}, v_n\}$ to a single specific frequency and growth rate.

- Reconstruction in the temporal domain is achieved by selecting the frequencies and reconstructing.

Manifestation of Period Doubling Bifurcation

Nature of the subharmonic frequency



- DMD assists in extracting the flame structure at the subharmonic frequency of interest.
- Under the effect of PVC: azimuthal convection of high heat release disturbance, wherein intensity is skewed towards the right half of the cylinder.

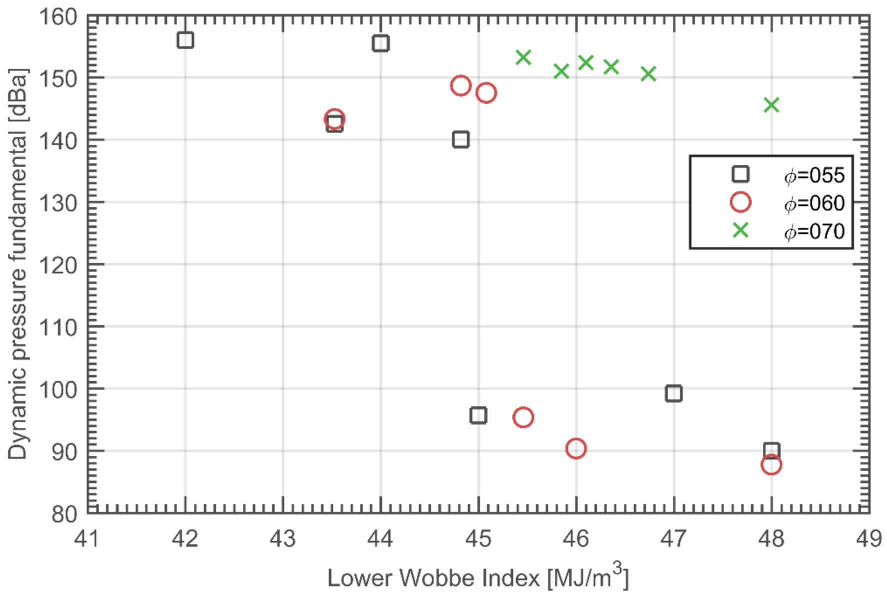
Interpretation of what triggers the Combustion instabilities

Research aim 1: Interpretation of what triggers the Combustion instabilities

- This section interprets the triggering mechanisms of combustion instabilities.
- The combustor is driven through Quiescence-Intermittency-Limit Cycle dynamics by enriching methane with hydrogen.
- It will be shown that the hydrogen molar content increases the extinction strain rate (k_{ext}) of the premixture and this characteristic quantity can largely collapse the transitions.
- Link between thermoacoustic dynamics and flame front curvature.

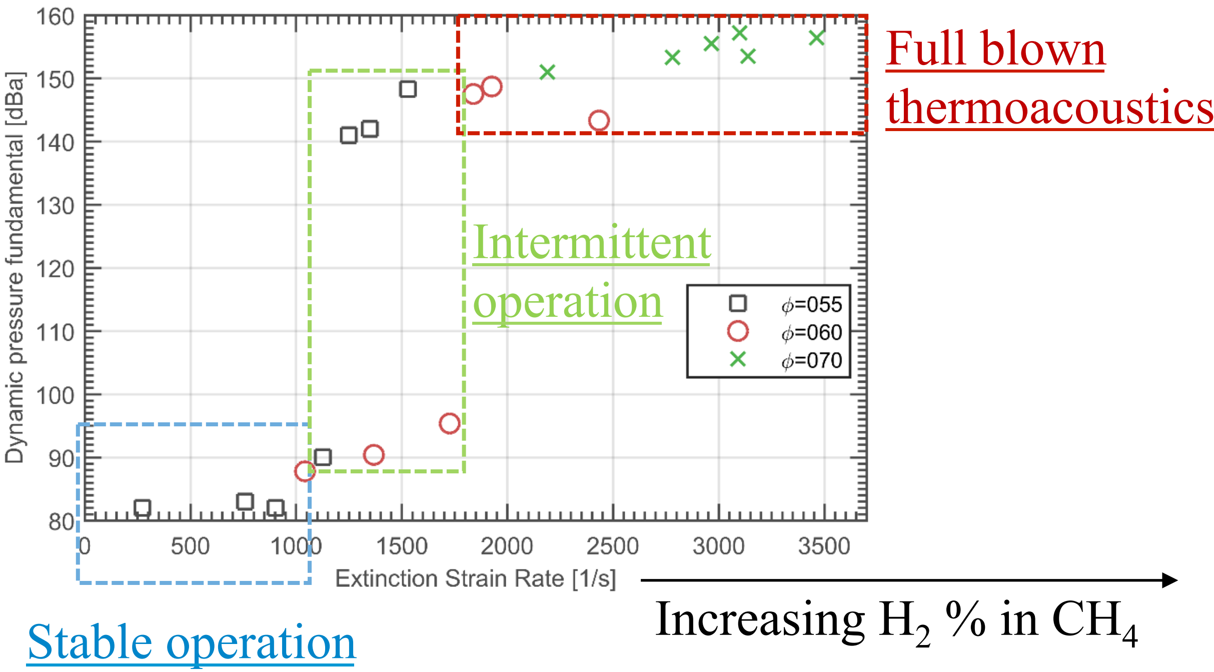
Motivation: Extinction strain rate is a mixture property collapsing dynamic state transitions (H_2 enriched CH_4 blends)

Collapsing dynamics with Wobbe index



Lower Wobbe Index $\mathrm{LWI} = LHV/\sqrt{SG}\ \ [MJ/m3]$

Collapsing dynamics with extinction strain rate



Karlis, E., Liu, Y. Hardalupas, Y., & Taylor, A. M. (2020) Extinction strain rate suppression of the precessing vortex core in a swirl stabilised combustor and consequences for thermoacoustic oscillations. Combustion and Flame, 211(3), 229-252.

Karlis, E., Liu, Y. Hardalupas, Y., & Taylor, A. M. (2019d) H_2 enrichment of CH_4 blends in lean premixed gas turbine combustion: An experimental study on effects on flame shape and thermoacoustic oscillations dynamics. Fuel, 254, 115524

Description of dynamic states: Focus on the intermittent regimes

Global operational quantities:

Bulk Reynolds number Re = 19000
Equivalence ratio ϕ=0.55

Mixture ID	Methane molar percentage $\chi:CH_4$	Hydrogen molar percentage $\chi:H_2$	Extinction Strain Rate [1/s]	Dynamic State	Le_χ
Case A	1.000	0.000	273	Susceptible to blow off	0.998
Case B	0.900	0.100	652	Quiescent, lifted	0.927
Case C	0.800	0.200	759	Quiescent, lifted	0.856
Case D	0.700	0.300	1127	Intermittent	0.784
Case E	0.650	0.350	1250	Intermittent	0.748
Case F	0.625	0.375	1350	Intermittent	0.731
Case G	0.600	0.400	1540	Limit Cycle	0.713

Presented sample dynamics acquired from Case D

Limit cycle dynamics examined based on case G

Isothermal flowfield and quiescent flame structure

Experimental Configuration
Isothermal-Particle Image Velocimetry (PIV) Measurements

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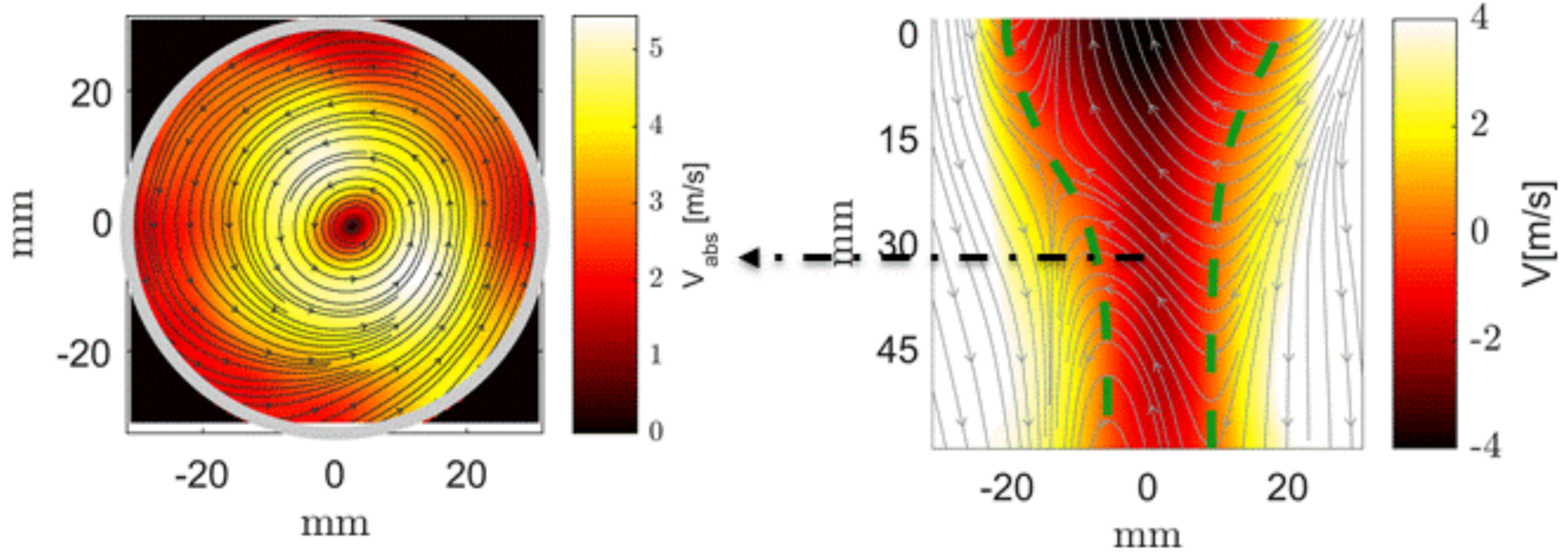
Azimuthal Radial FOV

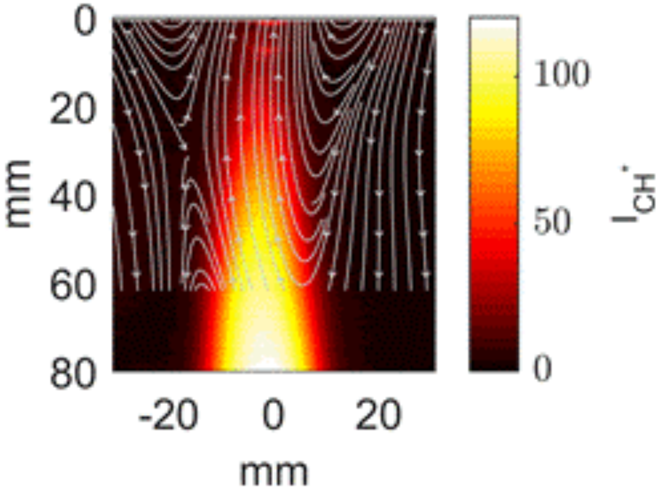
Axial radial FOV



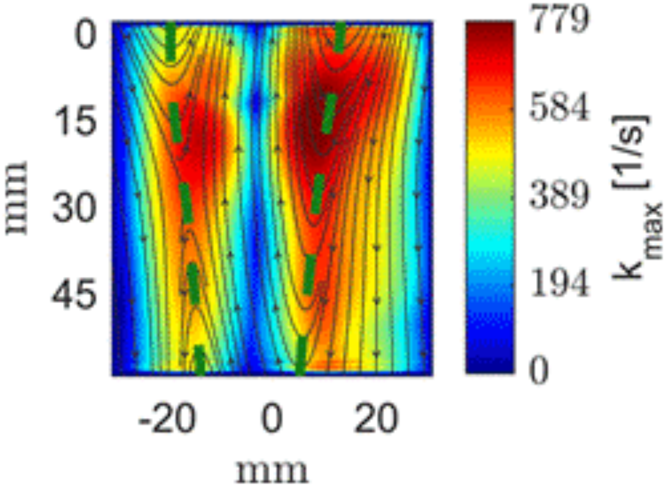
Axial-radial plane: isothermal flow features a recirculation zone with no downstream stagnation point, extending through all section of the PIV FOV

Experimental Configuration
Quiescent flame structure

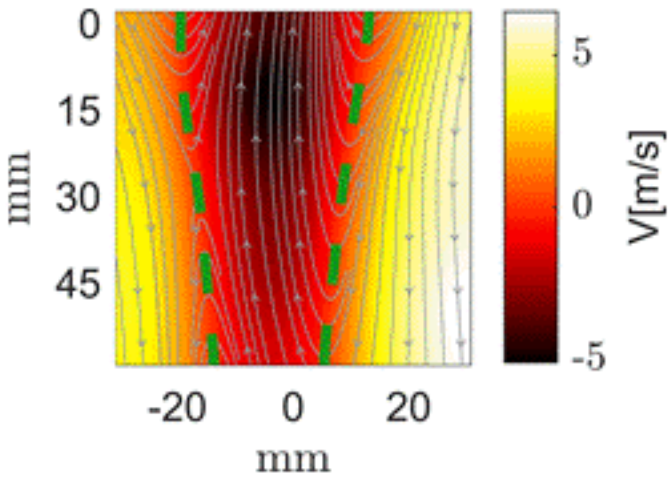
Quiescent flame



Axial-radial strain rate

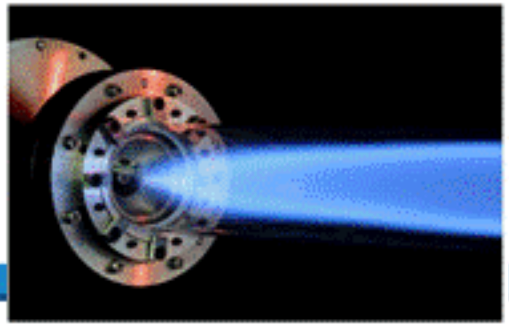


Axial Velocity



Long exposure image of a stable lean and elongated flame

- Flow structure similar to the isothermal.
- Flame anchoring within low strain rate regions



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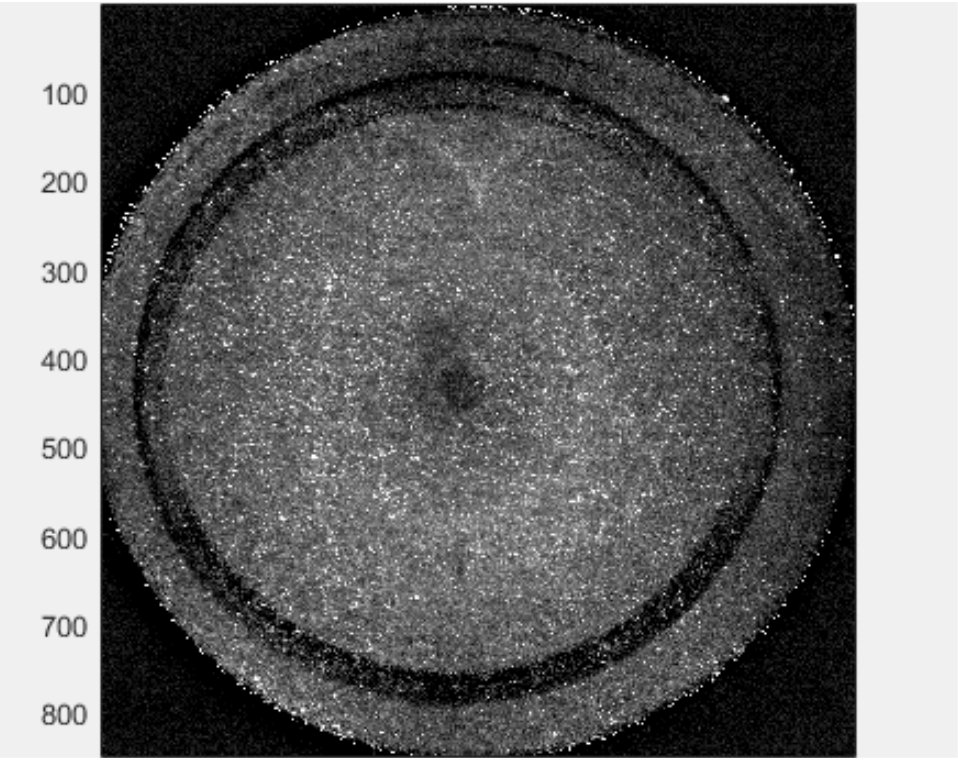
Experimental Configuration

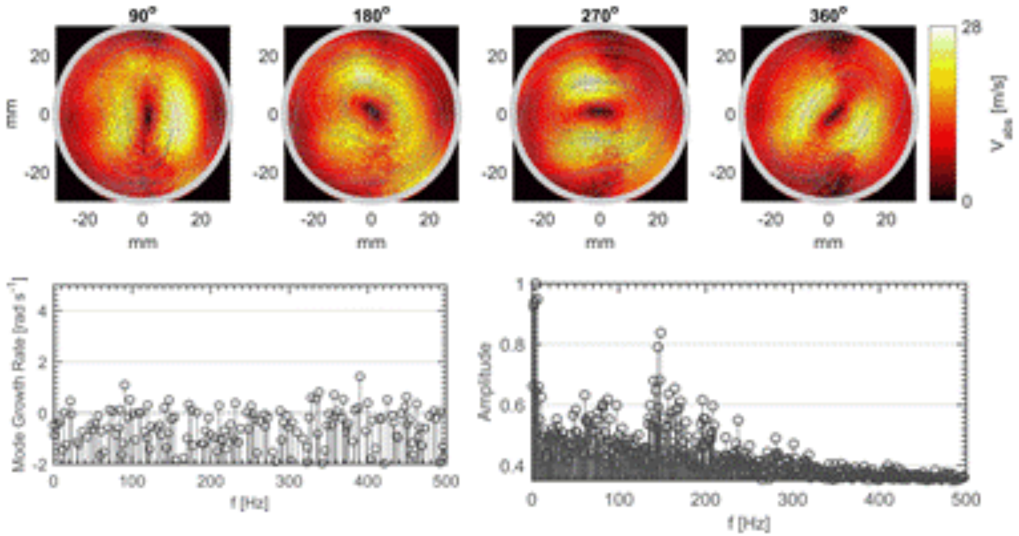
Isothermal flowfield dynamic coherent structures (PVC)

Mie Signal



DMD Filtering at 140 Hz

DMD analysis



DMD growth rates

DMD amplitudes

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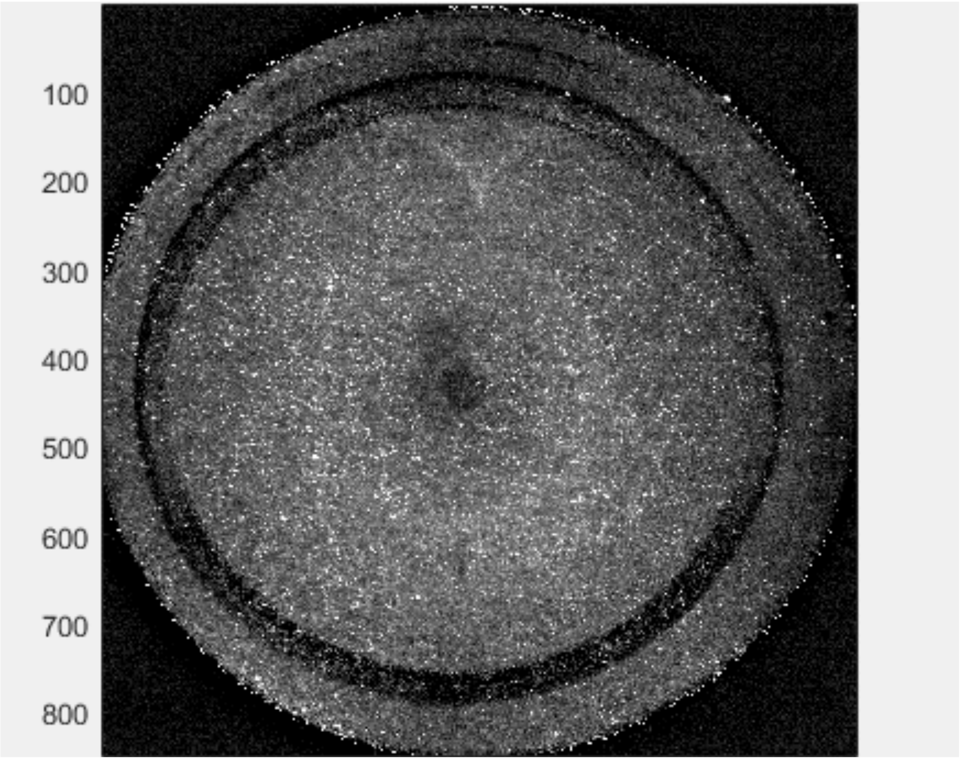
Experimental Configuration

Isothermal flowfield dynamic coherent structures (PVC)

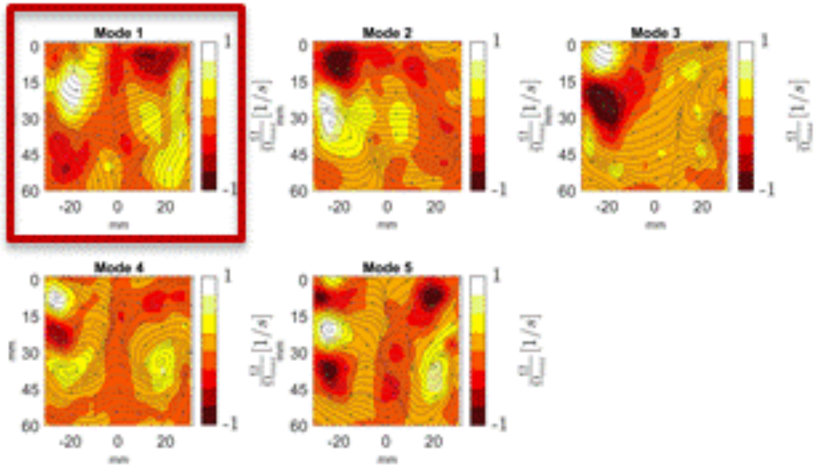
Mie Signal

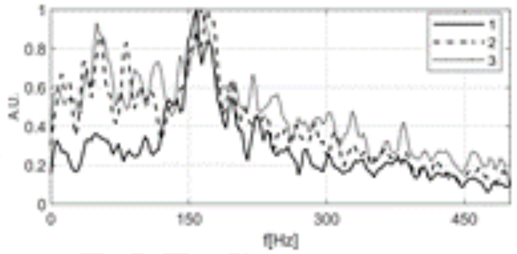


POD Modes (Normalized Vorticity)

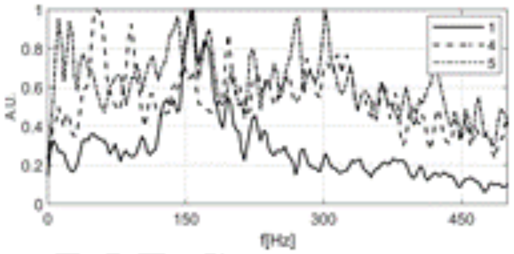
Wavemaker

POD analysis





POD Spectra Modes 1,2,3



POD Spectra Modes 1,4,5

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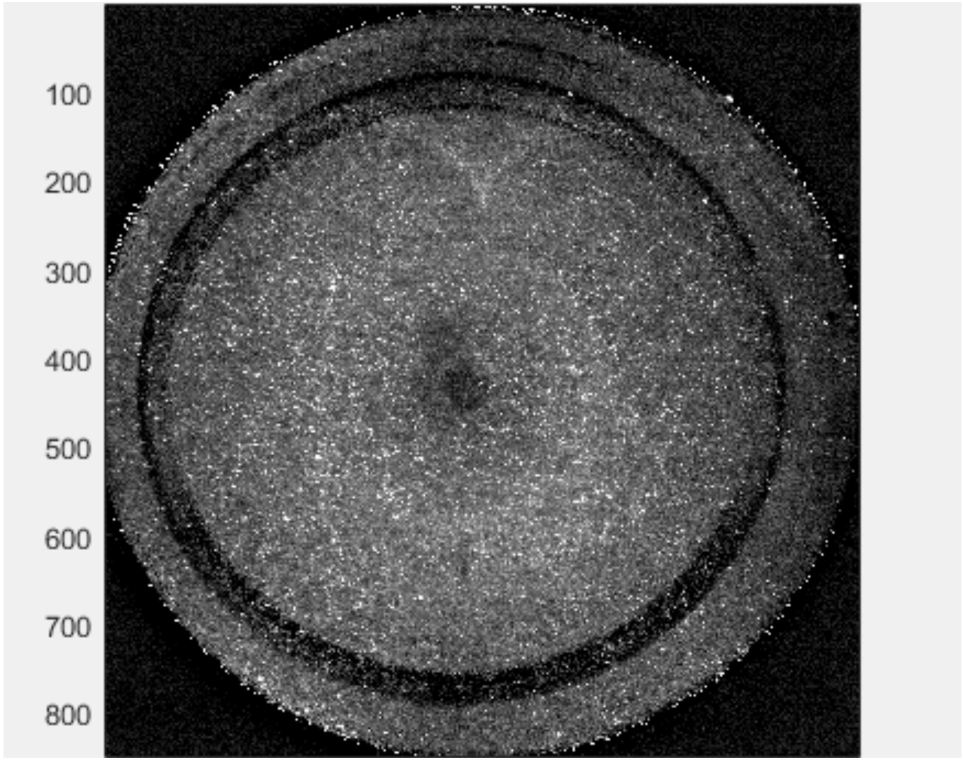
Experimental Configuration

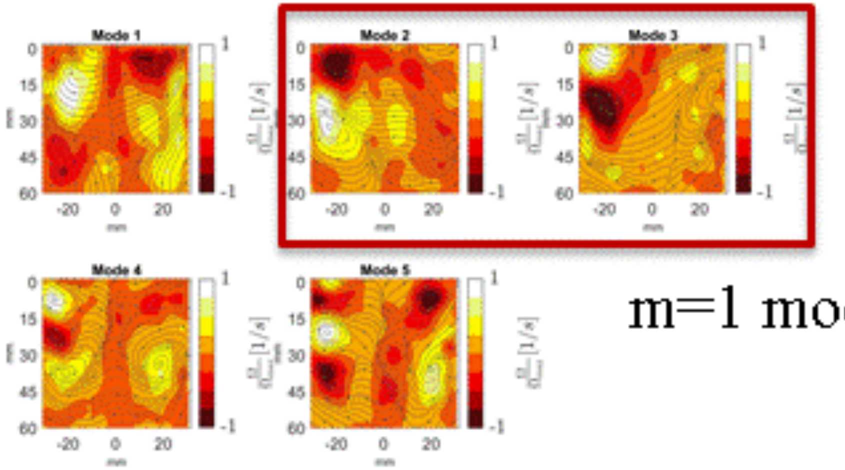
Isothermal flowfield dynamic coherent structures (PVC)

Mie Signal

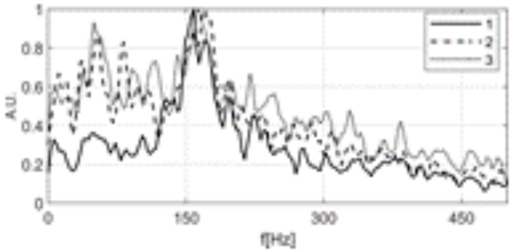


POD analysis

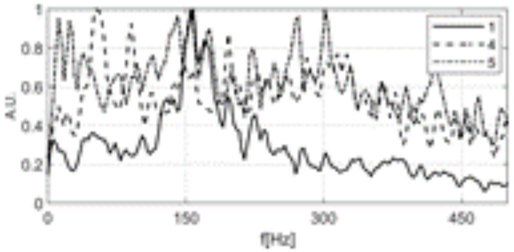
POD Modes (Normalized Vorticity)



m=1 modes



POD Spectra Modes 1,2,3



POD Spectra Modes 1,4,5

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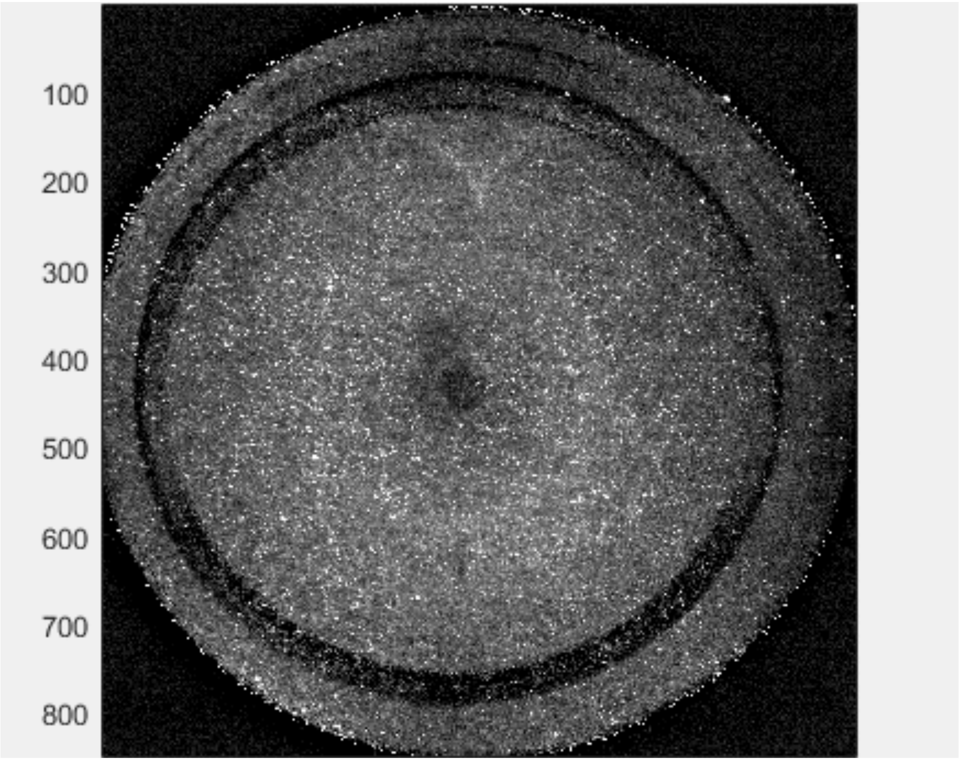
Experimental Configuration

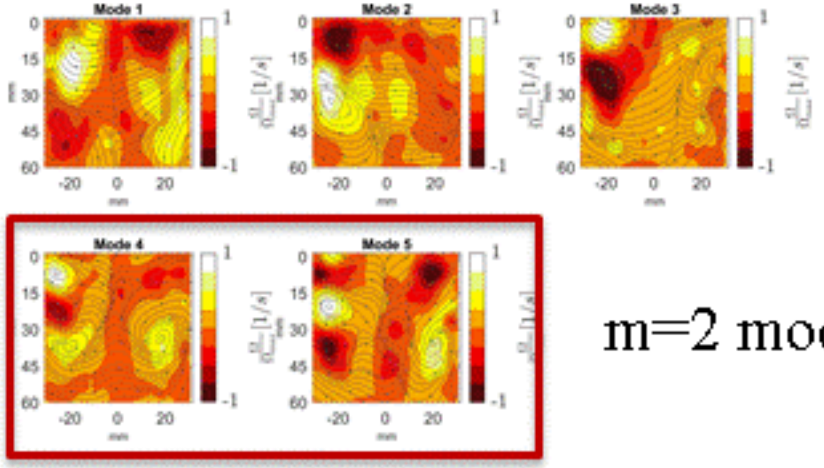
Isothermal flowfield dynamic coherent structures (PVC)

Mie Signal

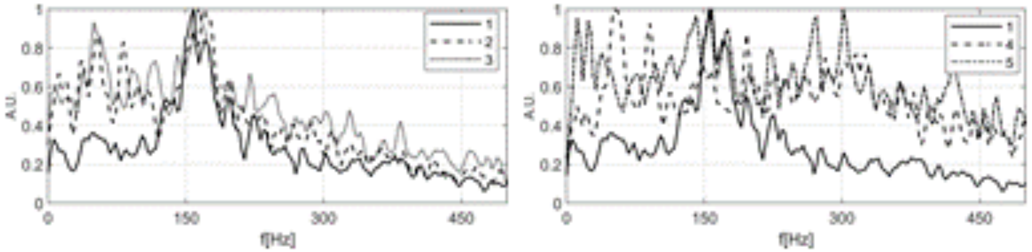


POD Modes (Normalized Vorticity)

POD analysis



m=2 modes



POD Spectra Modes 1,2,3

POD Spectra Modes 1,4,5

Intermittency: Interpretation of transitional dynamics
Phase space representation

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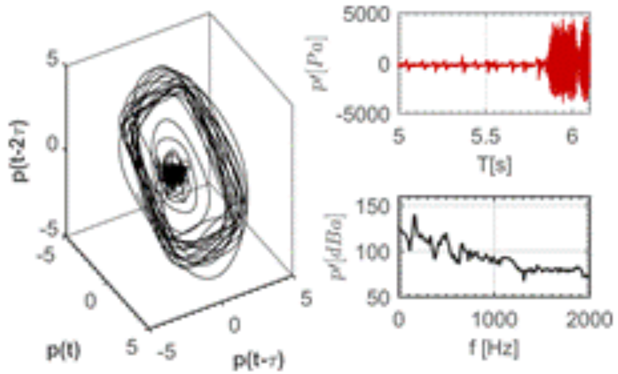
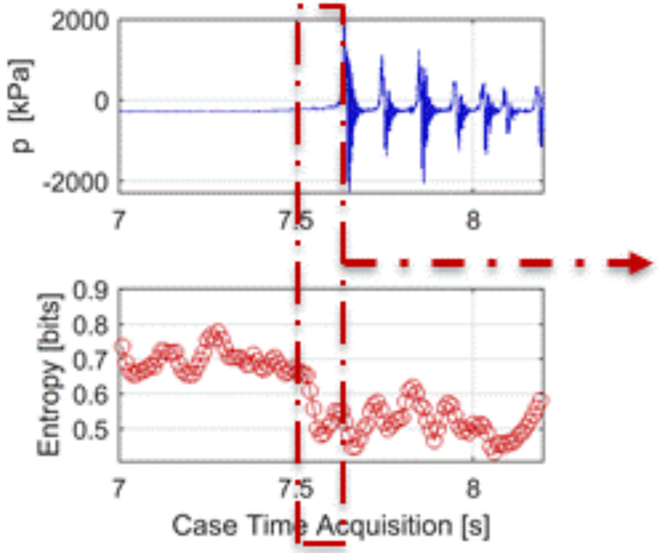
Case D: Permutation entropy used as a forewarning signal

Intermittency



Permutation Entropy (forewarning method)



Forewarning Period ~0.15s ~23 limit cycle periods (160 Hz)

- Short term prediction techniques such as the permutation entropy were employed to trigger the PIV system and record events before the transition into Hopf bifurcation.

Flame and flowfield structure during triggering of intermittent thermoacoustic bursts

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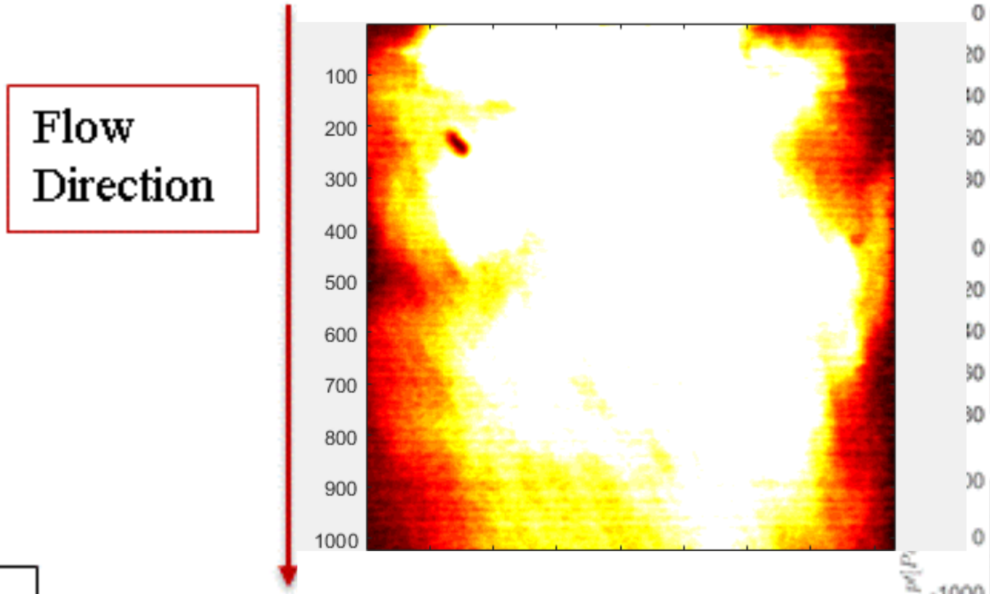
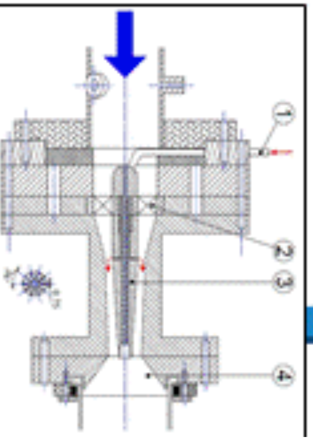
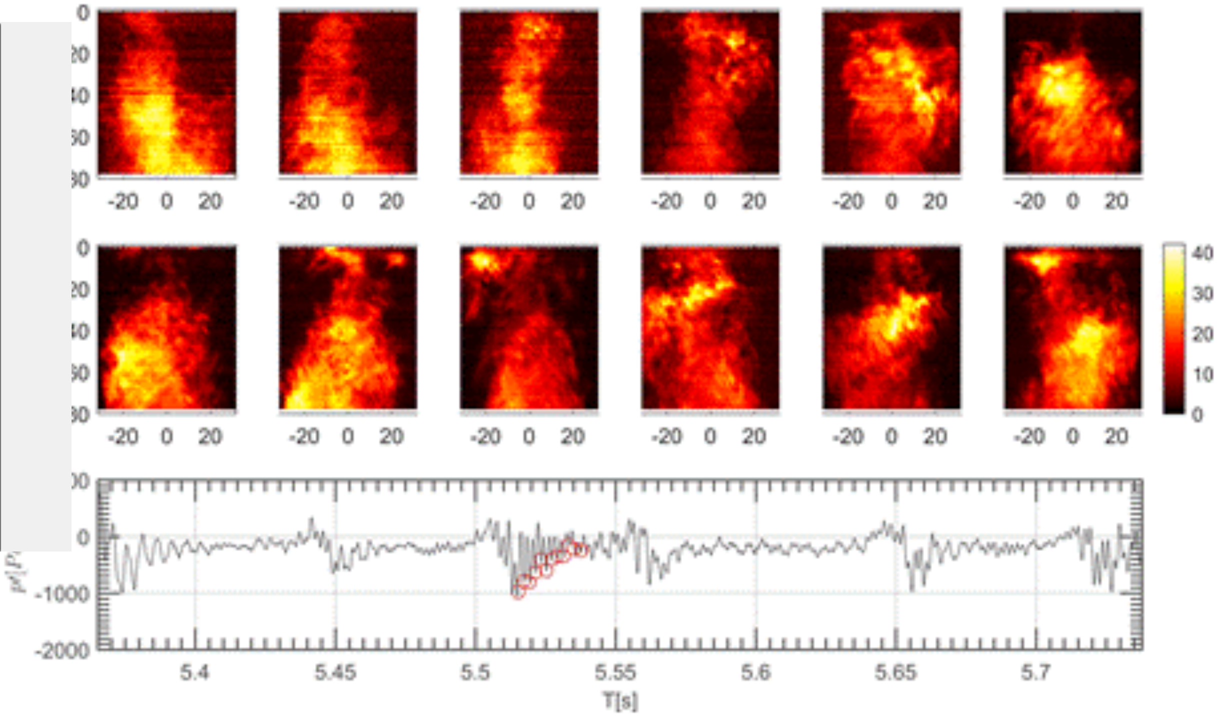
Description of dynamic state transitions
Instances of flame helical motion during thermoacoustic bursts





Intermittent Flame Dynamics

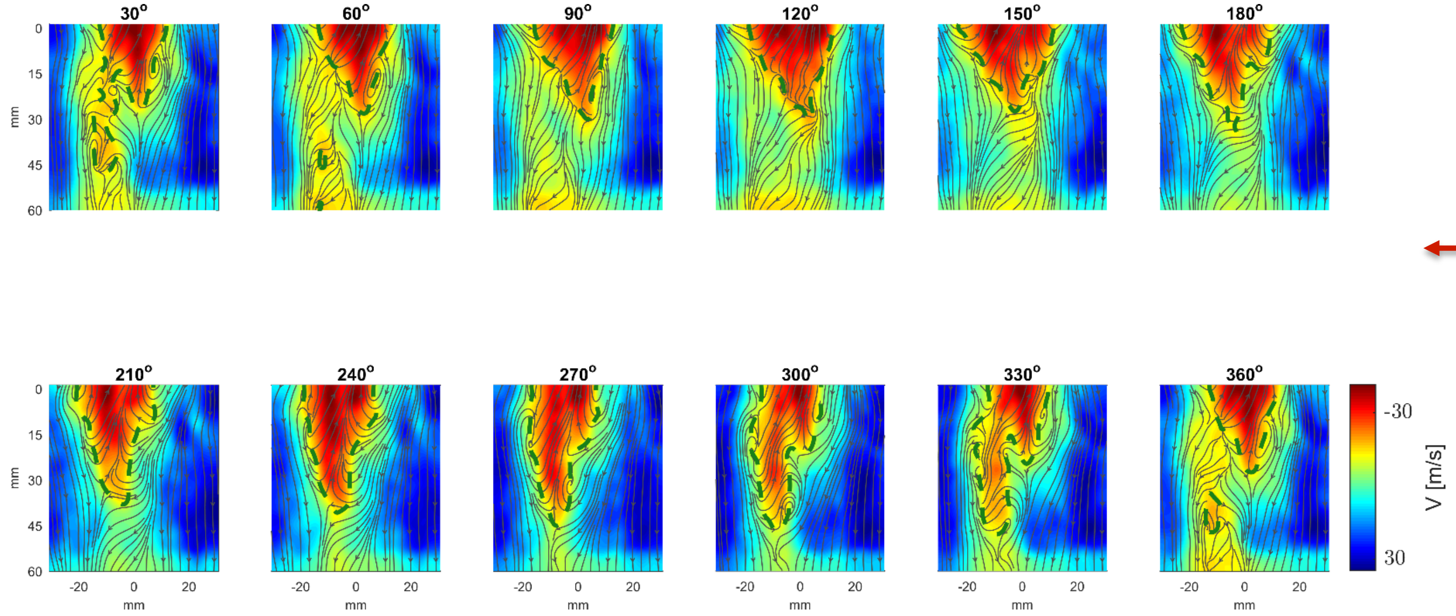


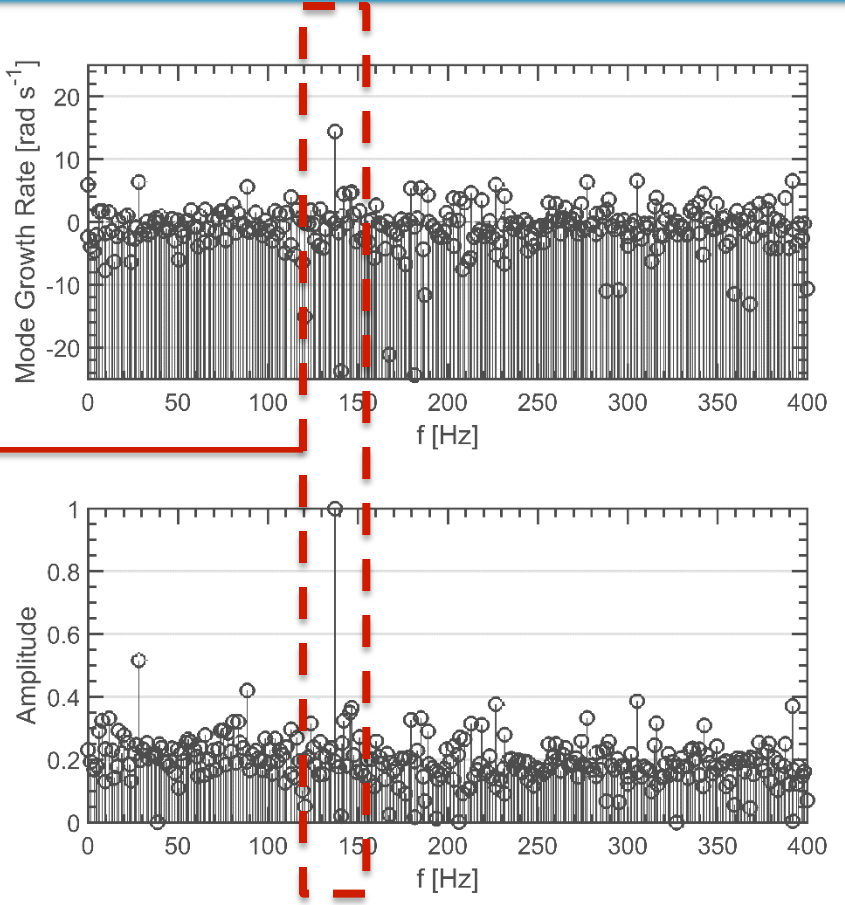
Dynamic pressure time series

Description of dynamic state transitions

Precession as extracted via DMD

Filtering via DMD: Frequency of precession is very close to the isothermal PVC frequency of precession





Frequency of precession: 137 Hz

Description of dynamic state transitions
Dynamic pressure phase space structure and intermittent flow dynamics

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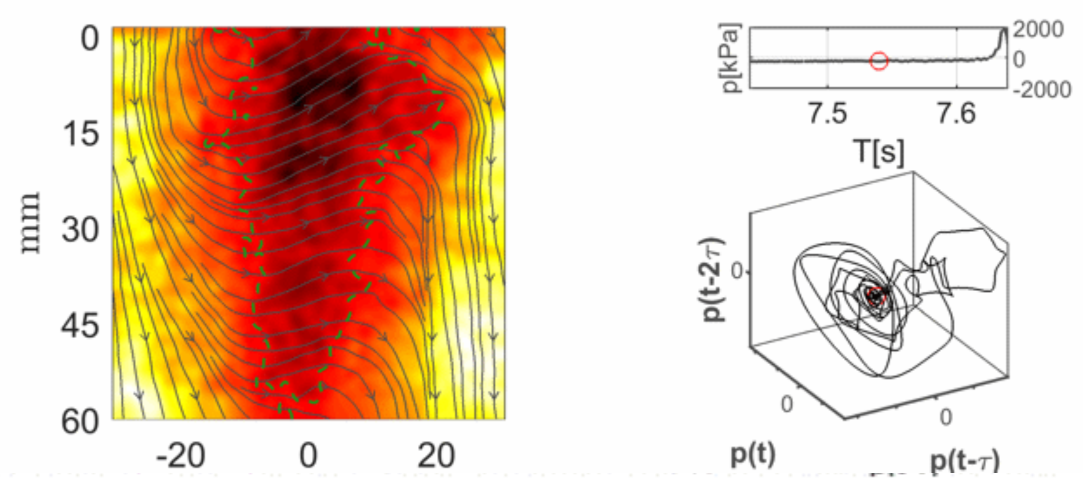
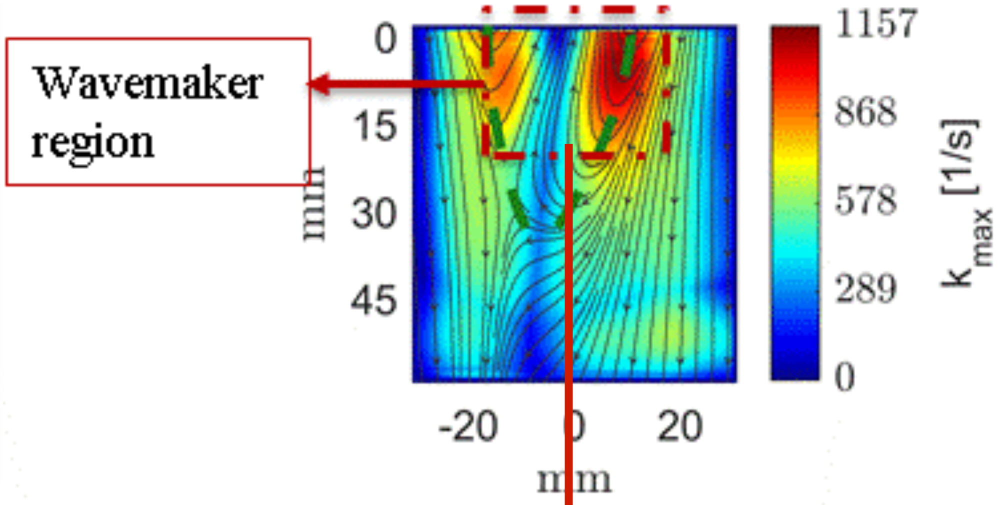
Intermittent Flow Dynamics



Contours of axial velocity

Mean strain rate (k_{flow}) during intermittency



If the elongated flame sustains straining such that is anchors close to the region wherein the helical wavemaker exists, then the flame precesses under the influence of the helical coherent structure (PVC)

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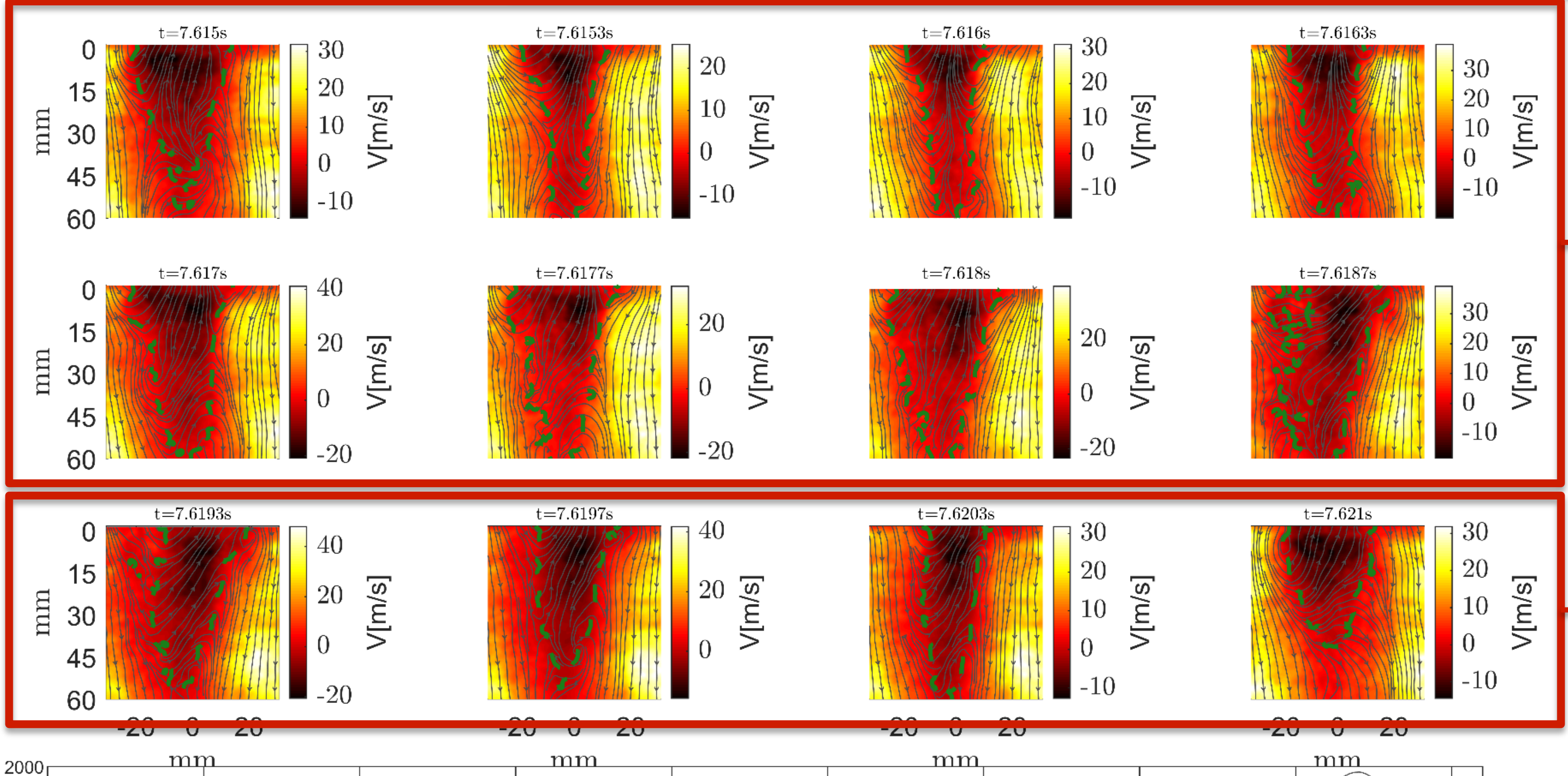
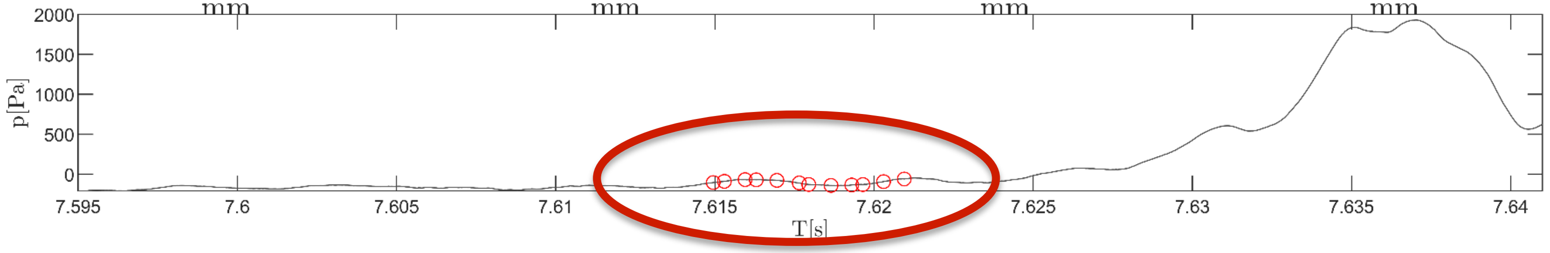
Description of dynamic state transitions

Breakdown of transition events: Pre-triggering



Initiation of helical motion of recirculation zone under the effect of helical coherent structures along the shear layers.

Initial formation of downstream axial stagnation point in the recirculation zone



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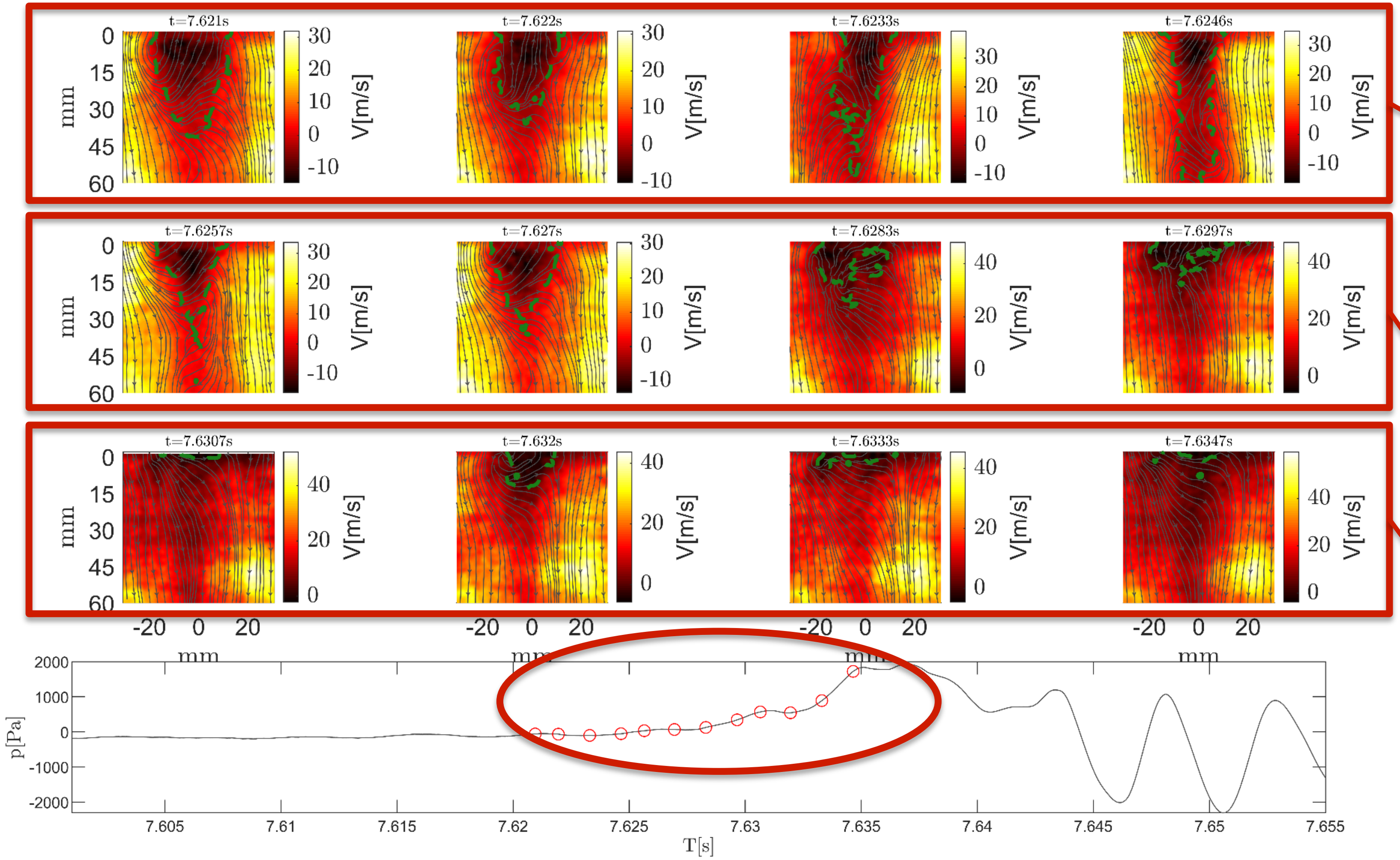
Description of dynamic state transitions

Breakdown of transition events: Thermoacoustic burst



Convection of high axial velocity amplitude disturbance causing the recirculation zone to form a downstream axial stagnation point.

The passage of the disturbance decreases the axial and radial extent of the recirculation zone.

When the axial extent of the recirculation zone is minimum the dynamic pressure is maximum

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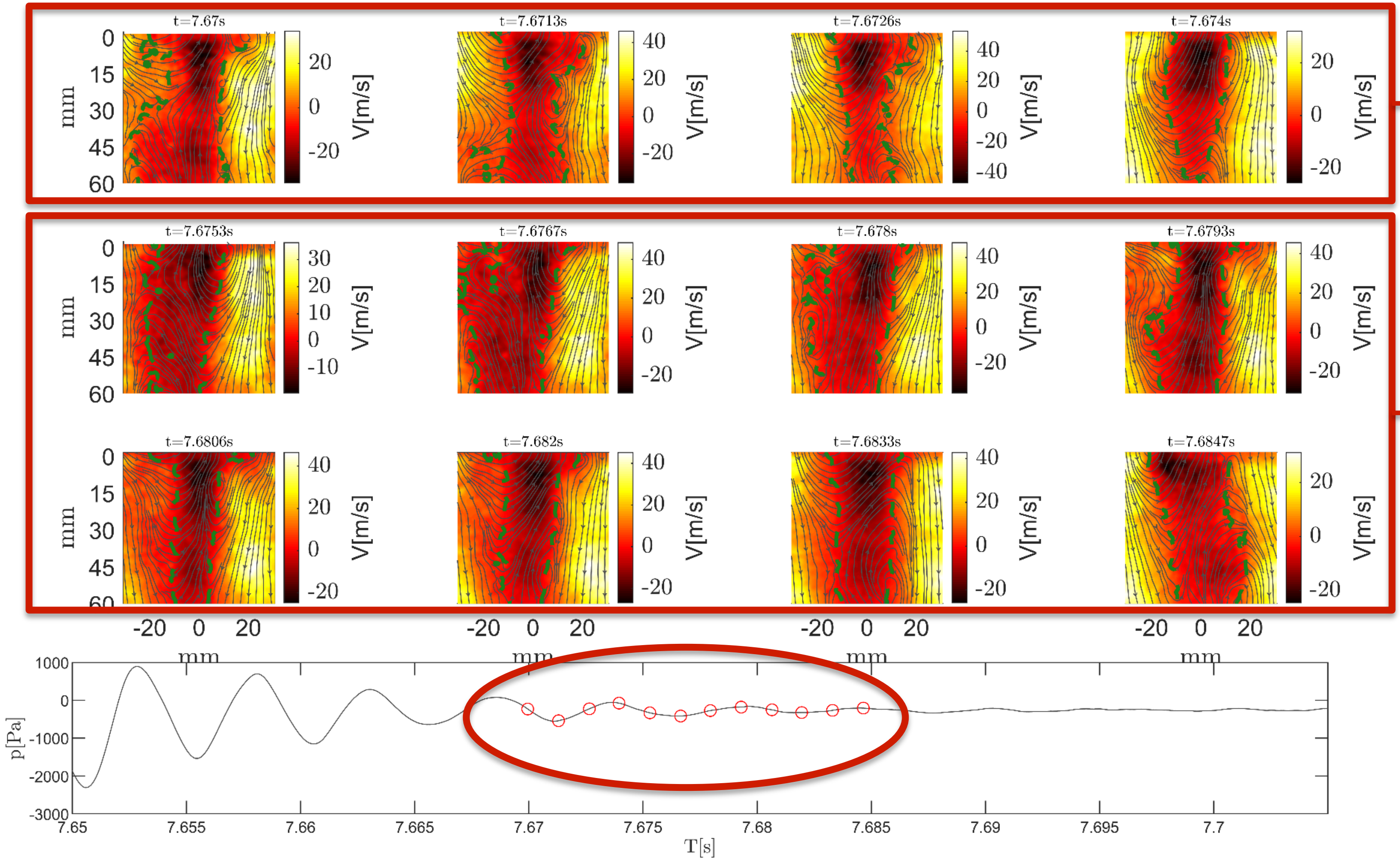
Description of dynamic state transitions

Breakdown of transition events: Requiescence



Decreasing rate of helical precession

Reestablishment of open ended recirculation zone with no downstream stagnation point

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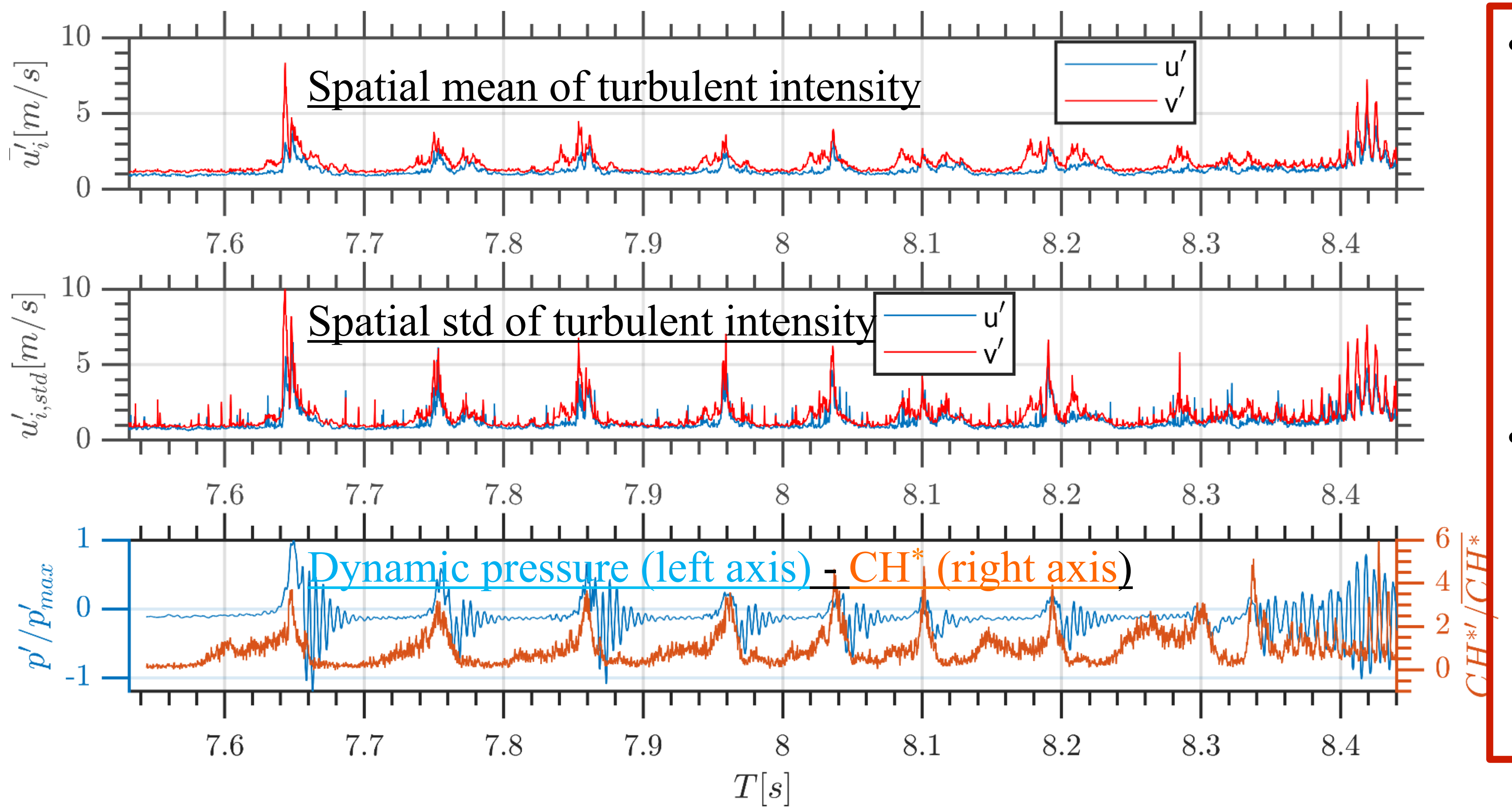
Description of dynamic state transitions

Spatial mean and standard deviations of turbulent intensity



- The spatial mean and standard deviations of the turbulent intensities of the flowfield demonstrate spikes that coincide with the thermoacoustic bursts.

- The burning rate increases and the range of scales, with which the flame interacts, widens upon transitioning into thermoacoustic instability.

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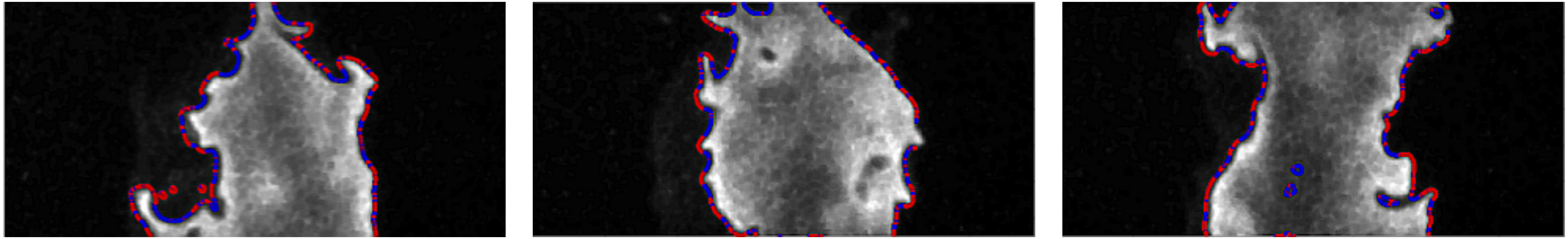
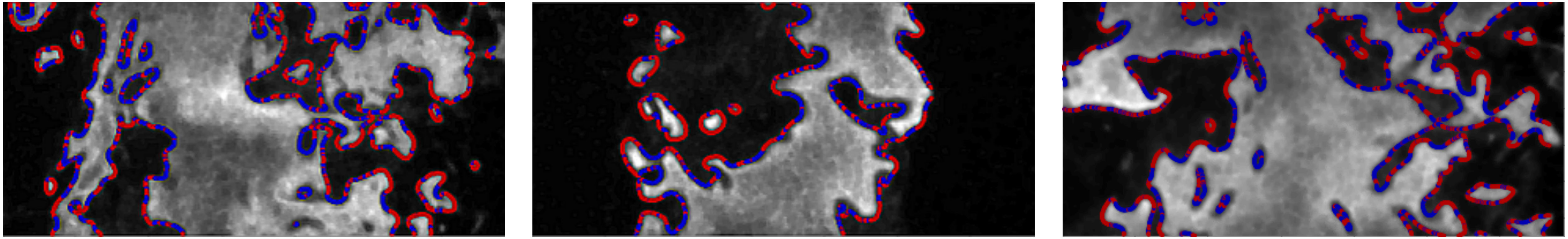
Description of dynamic state transitions

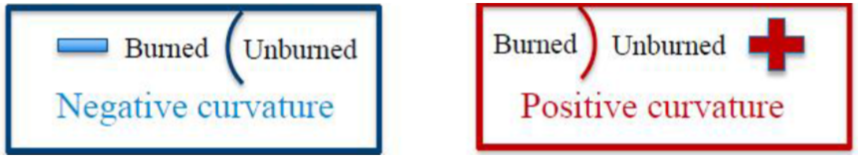
Flame front curvature characteristics of intermittent flame via OH-PLIF measurements

Quiescent flames-straight and elongated.



Transitional flames-more wrinkled and with greater radial extent





Reminder: Curvature convention

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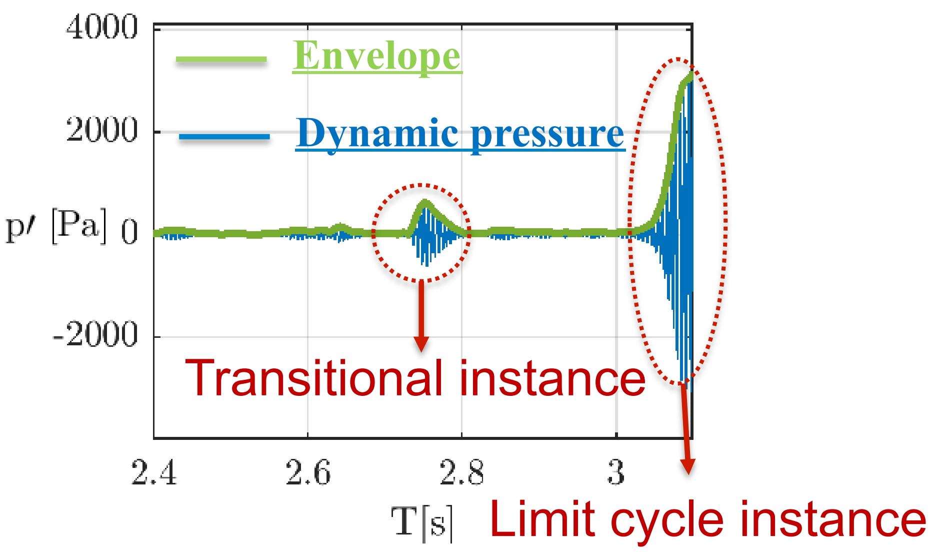
Description of dynamic state transitions

Flame front curvature characteristics of intermittent flame via OH-PLIF measurements



Case ID Thermoacoustic state	: Mean curvature	σ: Standard deviation	μ_3 : skewness	μ_4: kurtosis
D: Quiescent D: Transitional D: Limit Cycle	0.115 0.167 -0.036	1.108 1.128 1.416	0.091 0.095 -0.036	5.045 4.794 4.472
E : Quiescent E: Transitional E: Limit Cycle	0.127 0.087 -0.048	1.316 1.330 1.408	0.048 0.047 -0.031	5.125 4.755 4.577
F: Quiescent F: Transitional F: Limit Cycle	0.122 0.089 -0.024	1.264 1.296 1.402	0.027 0.028 -0.013	5.344 5.120 4.598

Distinction between dynamic states:
Quiescent: $p'_{envelope}$ < 300 Pa
Transitional: $p'_{envelope}$>300 Pa for at most 20 thermoacoustic cycles
Limit cycle: $p'_{envelope}$>300 Pa for at least 20 thermoacoustic cycles

Upon transitioning from quiescence towards a limit cycle:
Mean curvature decreases towards near zero negative values

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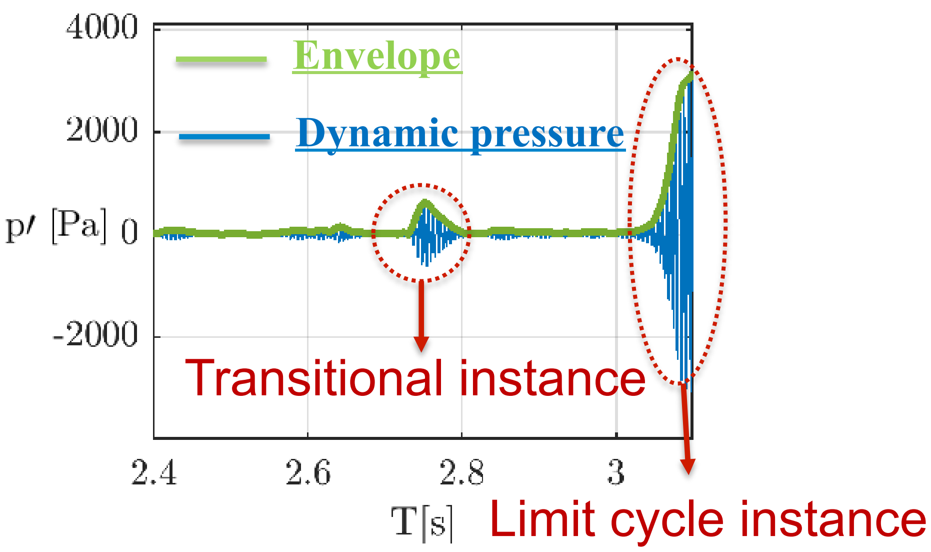
Description of dynamic state transitions

Flame front curvature characteristics of intermittent flame via OH-PLIF measurements



Case ID Thermoacoustic state	: Mean curvature	σ: Standard deviation	μ_3 : skewness	μ_4: kurtosis
D: Quiescent	0.115	1.108	0.091	5.045
D: Transitional	0.167	1.128	0.095	4.794
D: Limit Cycle	-0.036	1.416	-0.036	4.472
E : Quiescent	0.127	1.316	0.048	5.125
E: Transitional	0.087	1.330	0.047	4.755
E: Limit Cycle	-0.048	1.408	-0.031	4.577
F: Quiescent	0.122	1.264	0.027	5.344
F: Transitional	0.089	1.296	0.028	5.120
F: Limit Cycle	-0.024	1.402	-0.013	4.598

Distinction between dynamic states:
Quiescent: $p'_{envelope} < 300$ Pa
Transitional: $p'_{envelope} > 300$ Pa for at most 20 thermoacoustic cycles
Limit cycle: $p'_{envelope} > 300$ Pa for at least 20 thermoacoustic cycles

Upon transitioning from quiescence towards a limit cycle:
Standard deviation strongly increases.

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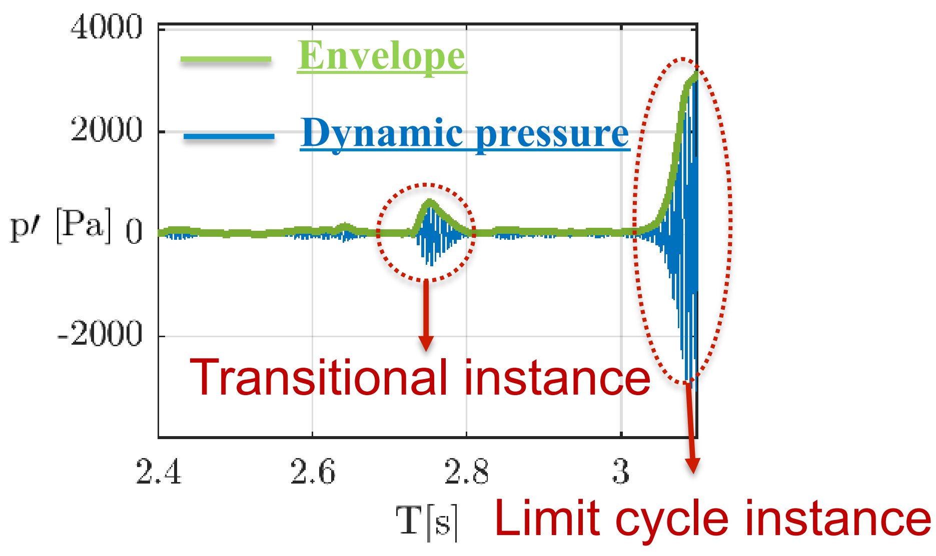
Description of dynamic state transitions
Flame front curvature characteristics of intermittent flame via OH-PLIF measurements



Case ID Thermoacoustic state	: Mean curvature	σ: Standard deviation	μ_3 : skewness	μ_4: kurtosis
D: Quiescent	0.115	1.108	0.091	5.045
D: Transitional	0.167	1.128	0.095	4.794
D: Limit Cycle	-0.036	1.416	-0.036	4.472
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F: Transitional	0.089	1.296	0.028	5.120
F: Limit Cycle	-0.024	1.402	-0.013	4.598

Distinction between dynamic states:
Quiescent: $p'_{envelope} < 300$ Pa
Transitional: $p'_{envelope} > 300$ Pa for at most 20 thermoacoustic cycles
Limit cycle: $p'_{envelope} > 300$ Pa for at least 20 thermoacoustic cycles

Upon transitioning from quiescence towards a limit cycle:
Standard deviation strongly increases.

Upon transitioning from quiescence towards a limit cycle:
Kurtosis decreases

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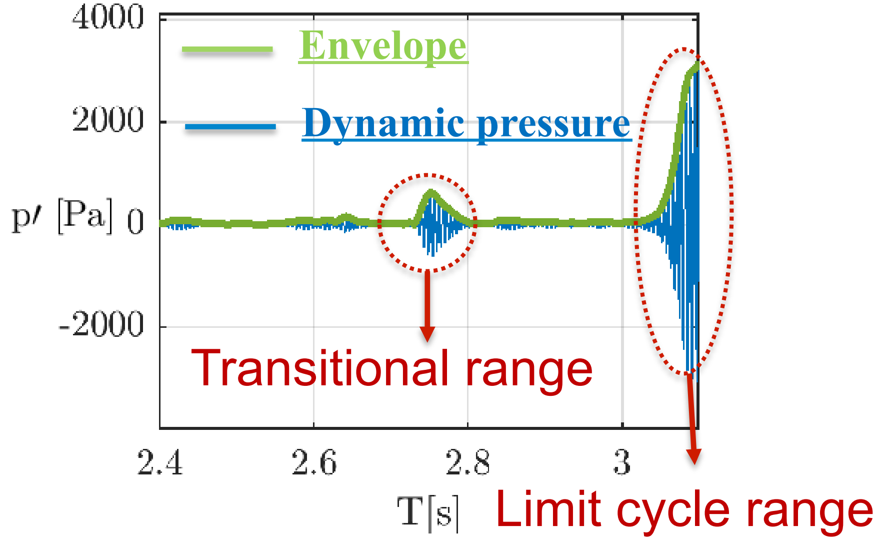
Description of dynamic state transitions

Flame front curvature characteristics of intermittent flame via OH-PLIF measurements



Case ID Thermoacoustic state	: Mean curvature	σ: Standard deviation	μ_3 : skewness	μ_4: kurtosis
D: Quiescent	0.115	1.108	0.091	5.045
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Distinction between dynamic states:
<u>Quiescent</u>: $p'_{envelope}$ < 300 Pa
<u>Transitional</u>: $p'_{envelope}$>300 Pa for <u>at most</u> 20 thermoacoustic cycles
<u>Limit cycle</u>: $p'_{envelope}$>300 Pa for <u>at least</u> 20 thermoacoustic cycles

<u>Flames that experience subcrical Hopf bifurcations gradually become more wrinkled while transitioning through the transitional thermoacoustic state towards the limit cycle.</u>

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Interpretation of limit cycle perpetuation mechanism

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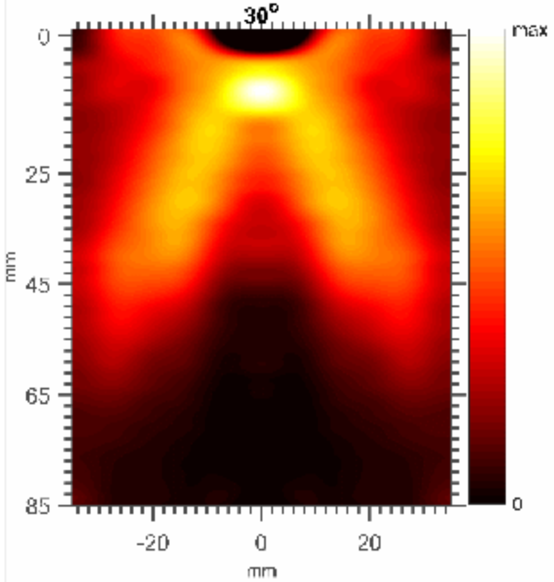
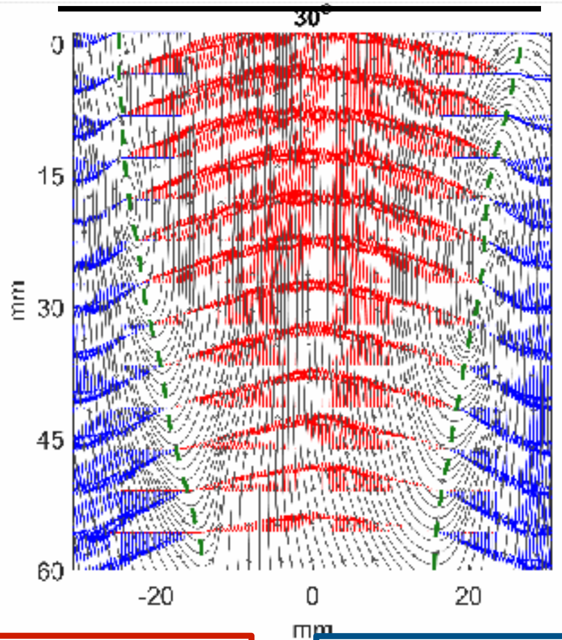
Limit Cycle structure
Case G (60% CH_4 – 40% H_2)

CH^* high speed imaging



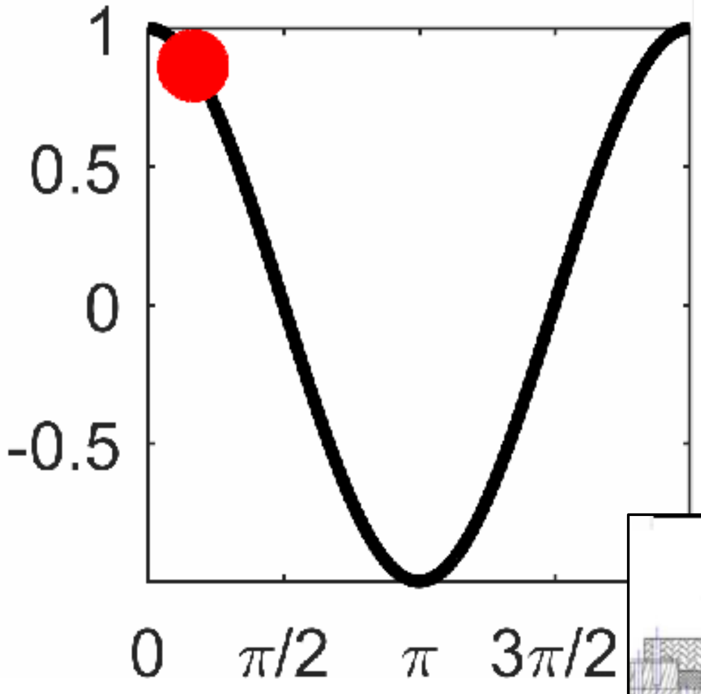
PIV measurements

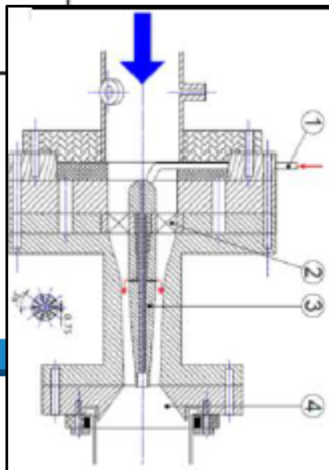


Recirculation Zone

Free Stream Velocity

Indicative dynamic pressure trace





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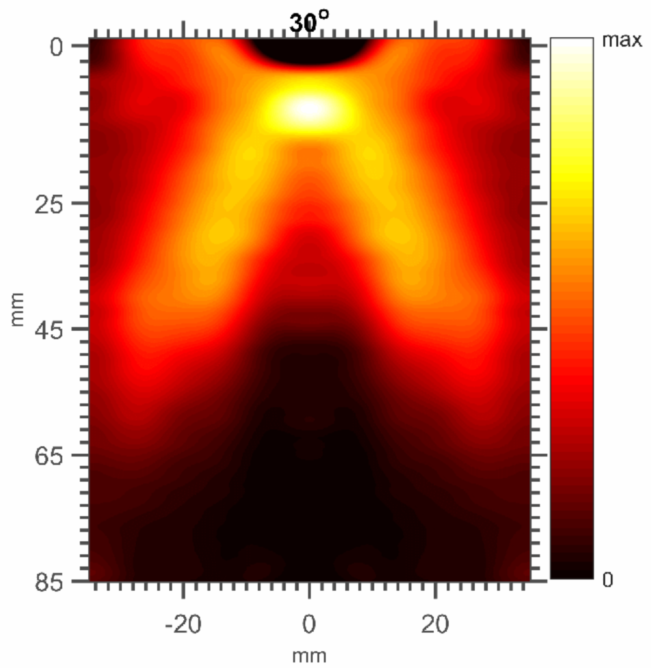
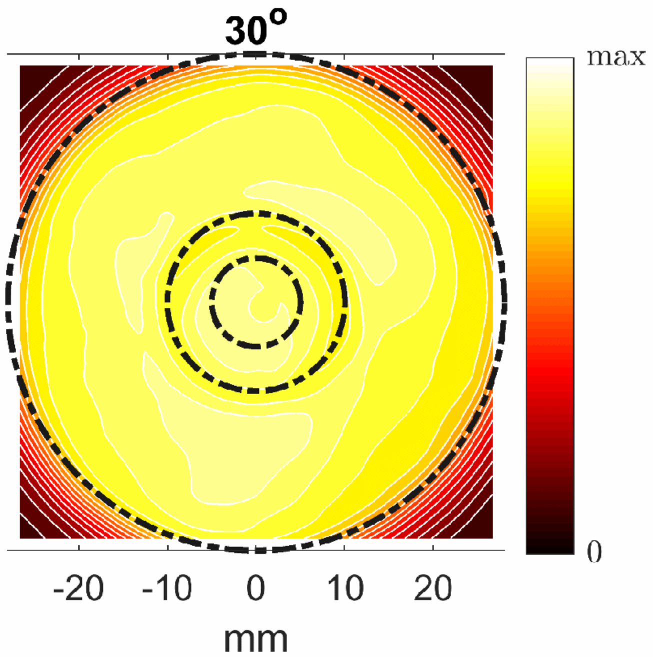
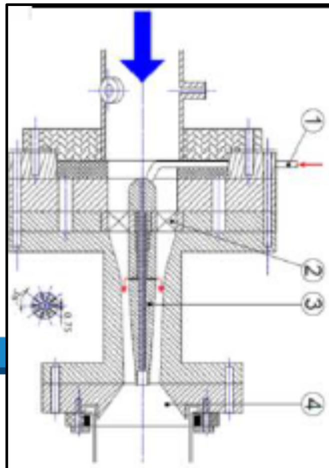
Limit Cycle structure
Case G (60% CH_4 – 40% H_2)

CH^* axial-radial



CH^* azimuthal-radial





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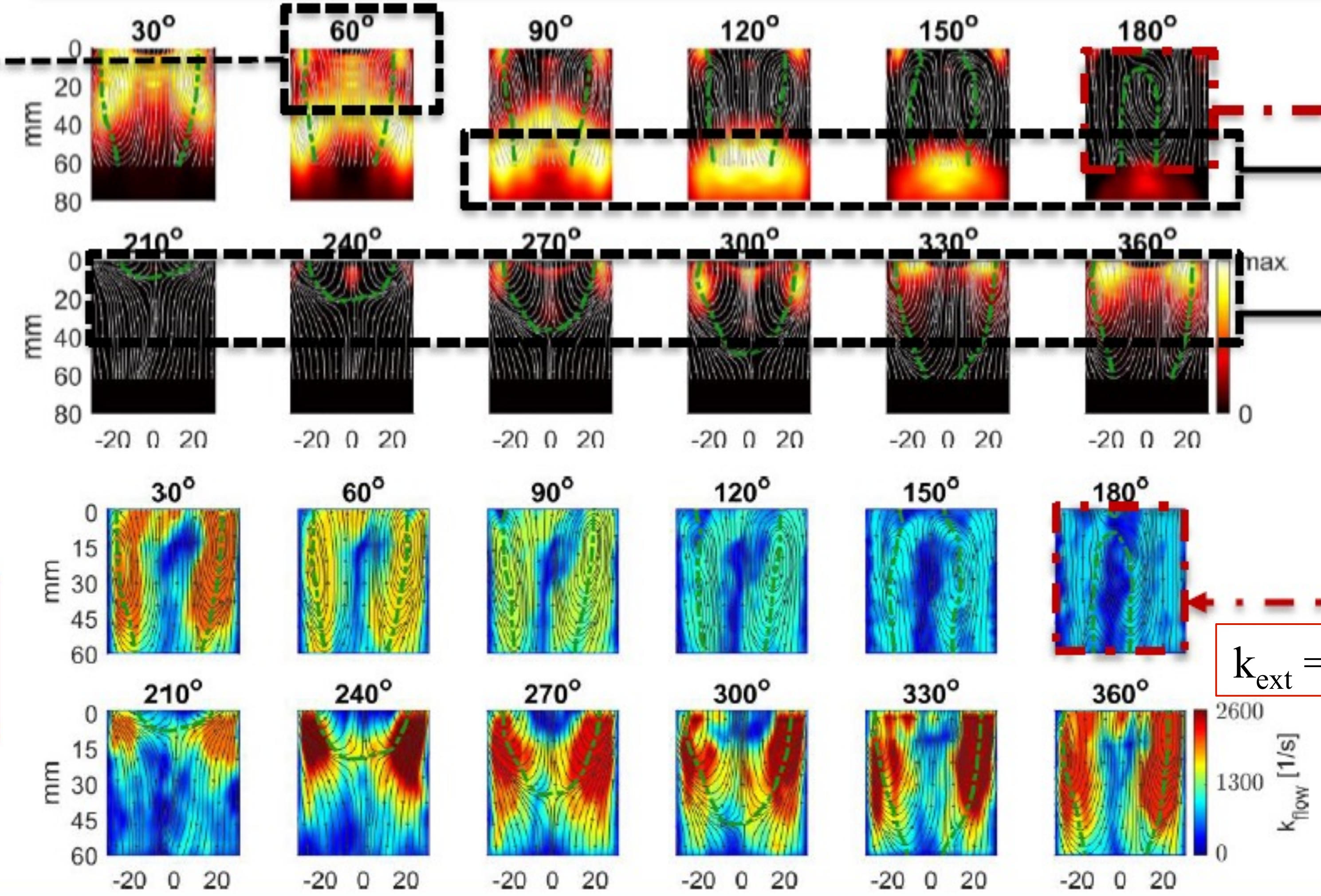
Limit Cycle structure
Cage G (60% CH_4 – 40% H_2)

Initiation of local extinction

Phase averaged I_{CH}^*

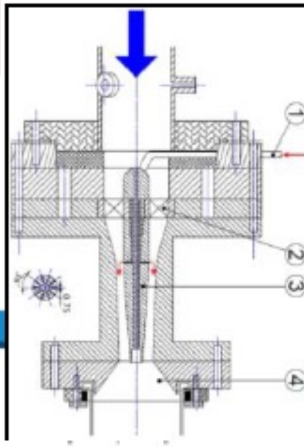
Phase averaged strain rate (k_{flow})



Convection of residual flame the mean flow

Flame propagating along inner shear layers

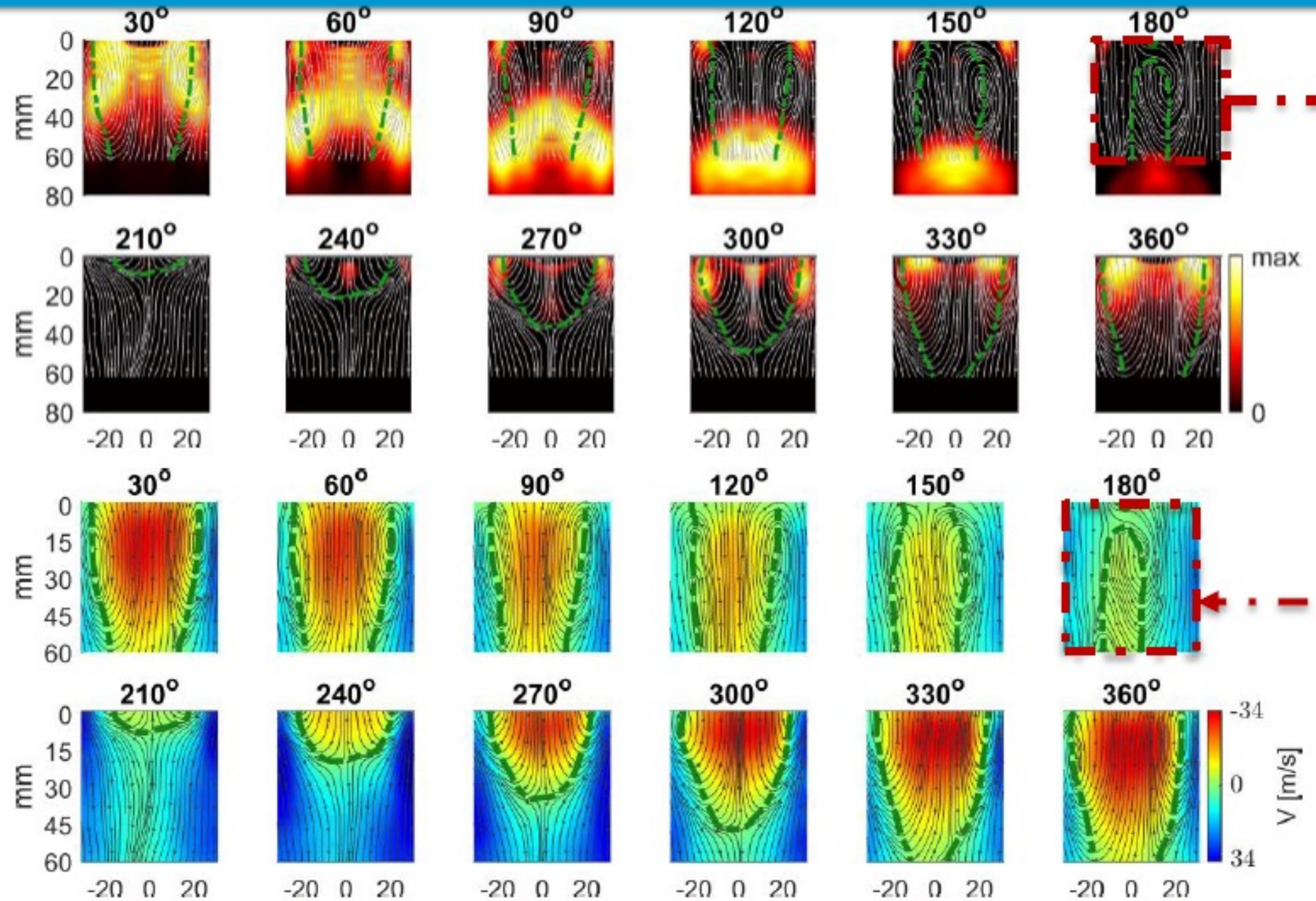
k_{ext} = 1540 1/s



Limit Cycle structure
Case G (60% CH_4 – 40% H_2)

Phase averaged flame structure

Phase averaged axial velocity



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Summary: During a subcritical Hopf bifurcation, how does the flame and flowfield structure bifurcate?

- Intermittency is observed when the flame is able to penetrate and anchor in the "Wavemaker" region, close to the inlet of the burner. To do so the flame needs to overcome increased strain rates in this region of the flowfield.
- <u>Flames tolerant to extinction strain rates are more susceptible to demonstrating subcritical Hopf bifurcations.</u>
- Transition into instability in the model gas turbine combustor is associated with:
    1. the PVC which imposes helical disturbances on the flame and the recirculation zone.
    2. Loss of randomness in the dynamic state: employed to forewarn of triggering.
- The role of the PVC is crucial. It exists both for the isothermal and the quiescent flowfields and it can instigate thermoacoustic bursts that are promoted mainly by the flame-wall interactions.

Summary: During a subcritical Hopf bifurcation, how do the flame and flowfield structure bifurcate?

- The flames of thermoacoustic systems demonstrating subcritical Hopf bifurcations assume increasingly wrinkled states. This is supported by both PIV and PLIF measurements:
  1. The standard deviation of the turbulent intensities during the transition into thermoacoustic instability increases.
  2. The standard deviation and the kurtosis of the flame front curvature increase.
- The extinction strain rate plays an important role in the perpetuation of limit cycle thermoacoustic oscillations as well. It leads to successive extinction-reignition of the flame thus perpetuating the limit cycle.