Rotating Detonation Rocket Engine Development from the Air Force Research Laboratory

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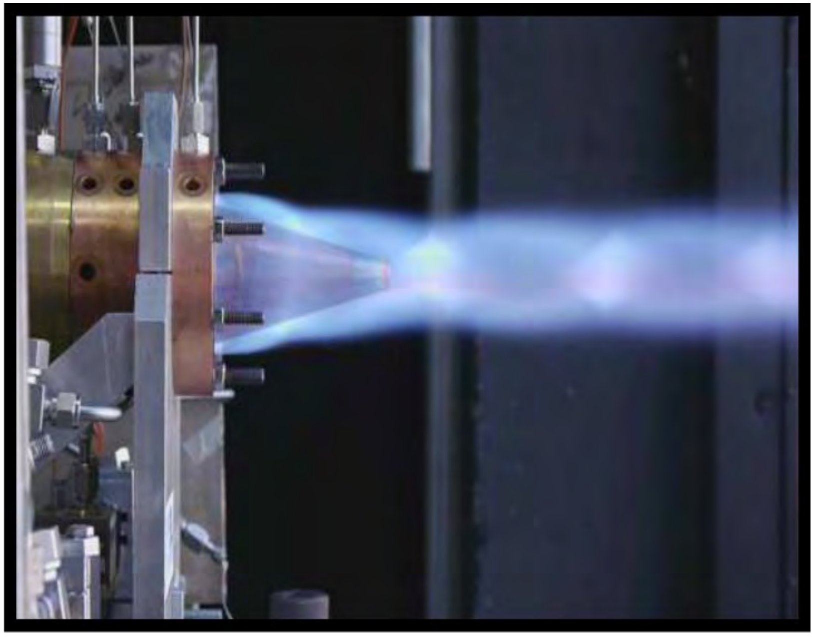
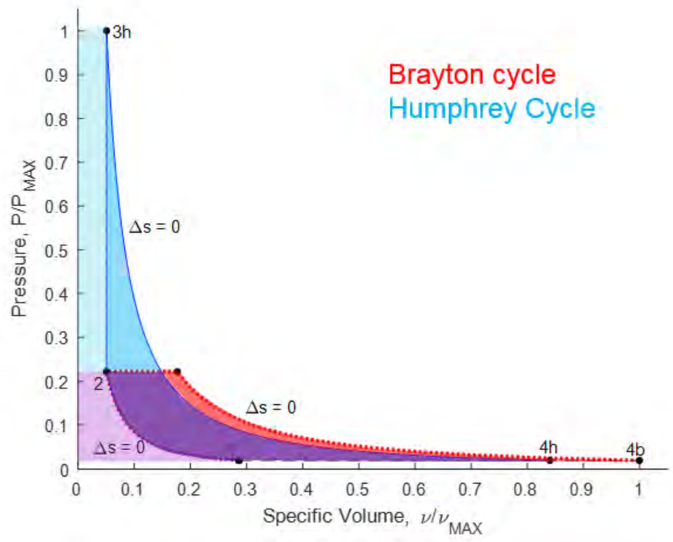
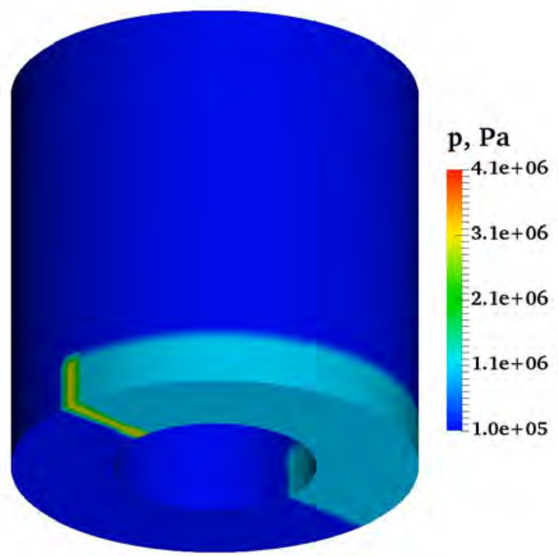
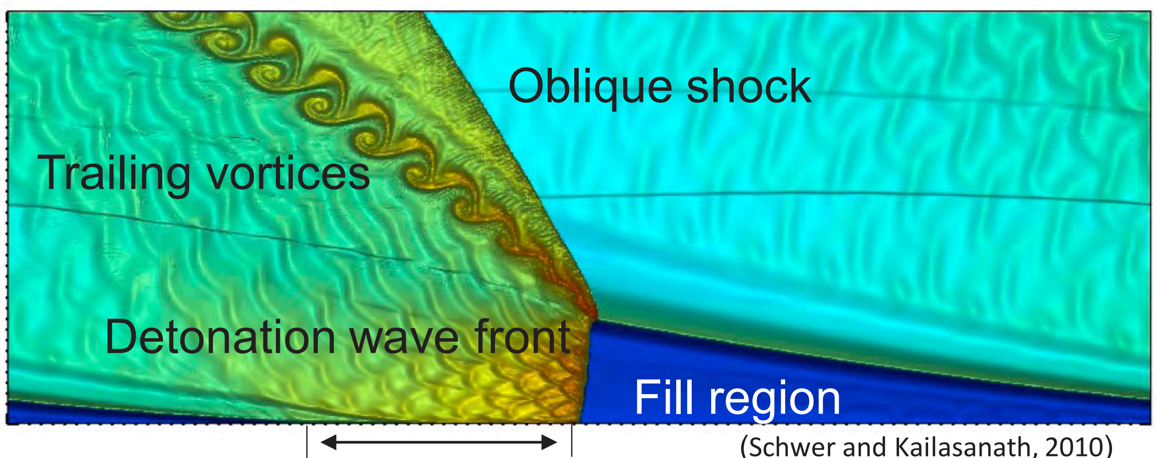


Rotating Detonation Rocket Engines



- **Pressure Gain Combustion**
  - Detonative combustion may provide pressure increase, resulting in higher efficiency or similar efficiency at lower pressures
  - 10-15% increase in theoretical efficiency or up to 5x reduction in initial combustion pressure
- **Rotating Detonation Rocket Engines (RDRE)**
  - Annular combustion geometry
  - Detonation wave travels continuously around channel
  - Mechanically simple and compact





(Schwer and Kailasanath, 2010)

Model RDRE Specifications

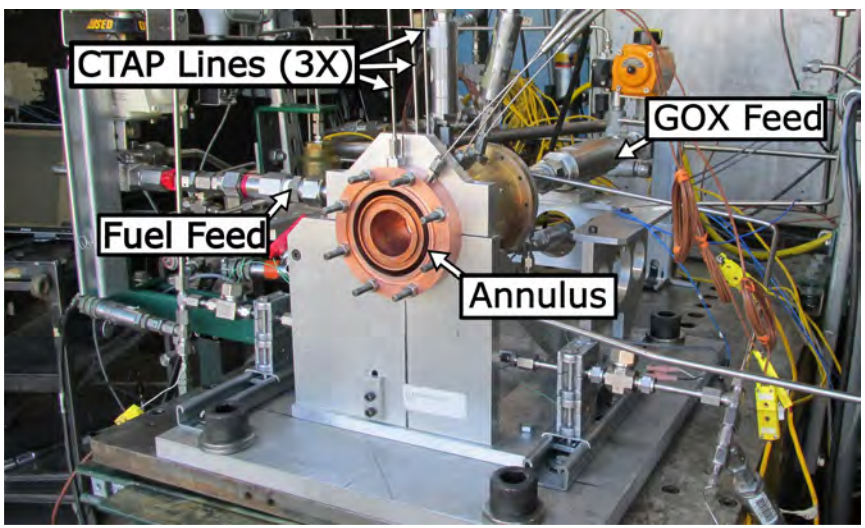
Specifications

- Annular geometry:
  - 3” (76.2 mm) diameter
  - 3” (76.2 mm) length
  - 0.2” (5 mm) channel width
- 72 unlike impinging injector elements
- Propellants: gas-gas, CH_4/GO_2
- Pre-detonator: CH_4/GO_2

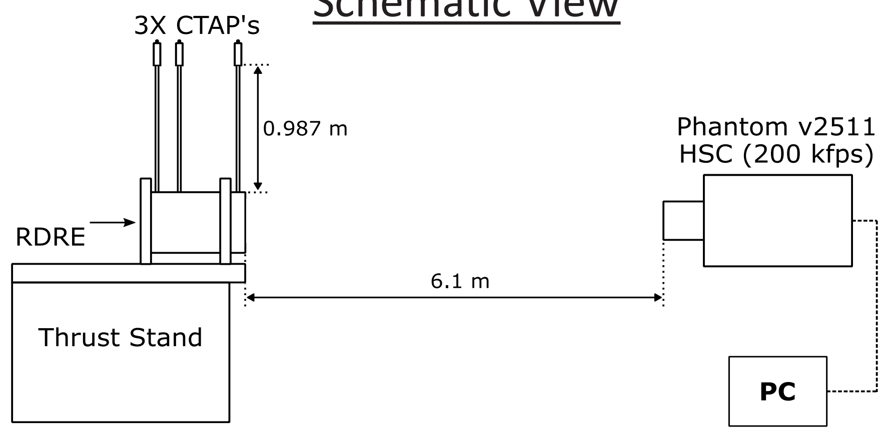
Measurements

- Thrust, Isp
- Mass flow (fuel/ox.)
- Plenum pressures (fuel/ox.)
- CTAP chamber pressure (3 axial locations)
  - (1) 0.35” (8.9 mm)
  - (2) 1.15” (29.2 mm)
  - (3) 2.58” (65.5 mm)
- 200 kfps visible imaging (direct view into annulus)

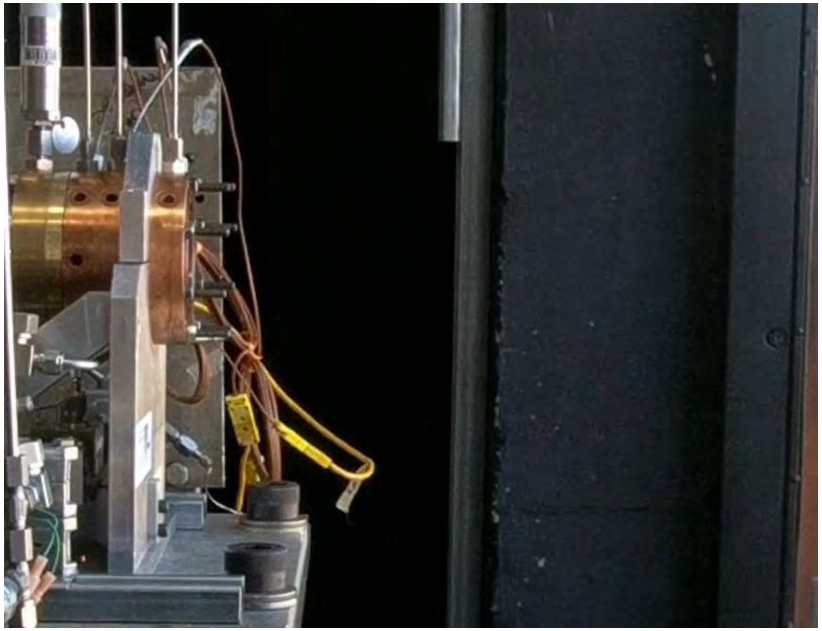
RDRE on Thrust Stand



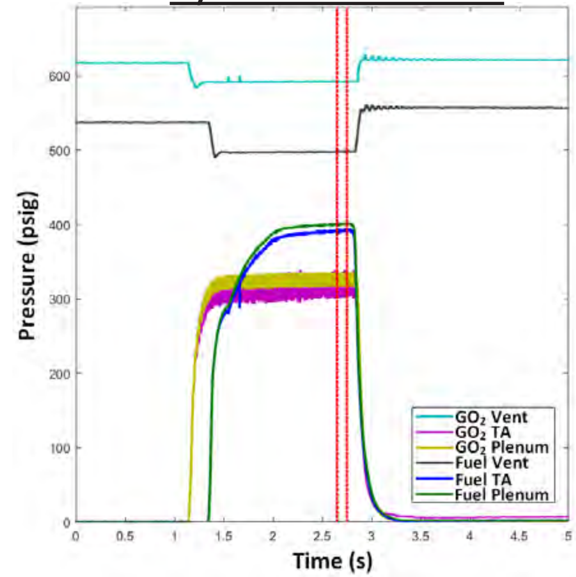
Schematic View



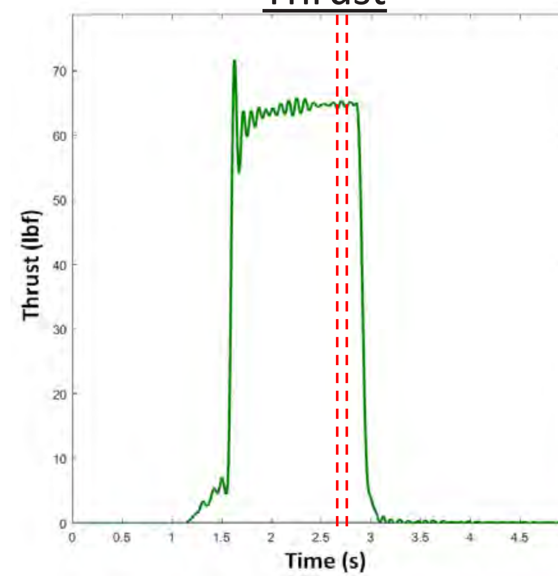
CH_4/O_2 Firing



System Pressures



Thrust

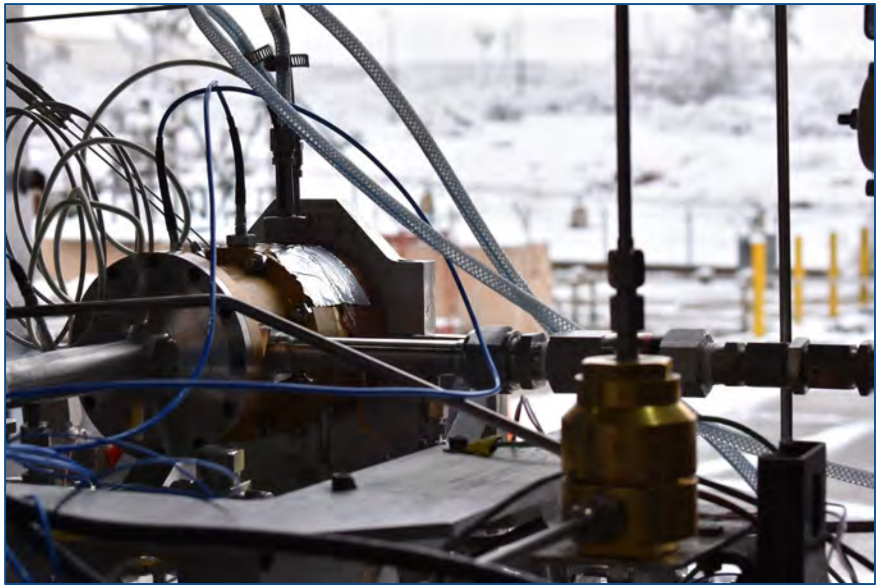


- ϕ = 1.1, $\dot{m}_{tot.}$= 0.6 lbm/s; Firing time of 1.25 seconds
- The last 100 ms of the test (bounded by the red lines) is the time duration for reported measurements.

Test Campaign Summary

Test Campaign 1.0 (2017-2018)

- Over 600 successful hot-fire tests
- Performance and operability examined for:
  - Increasing injector area (Pressure drop)
  - Variable reactant mixing (align/misalign)

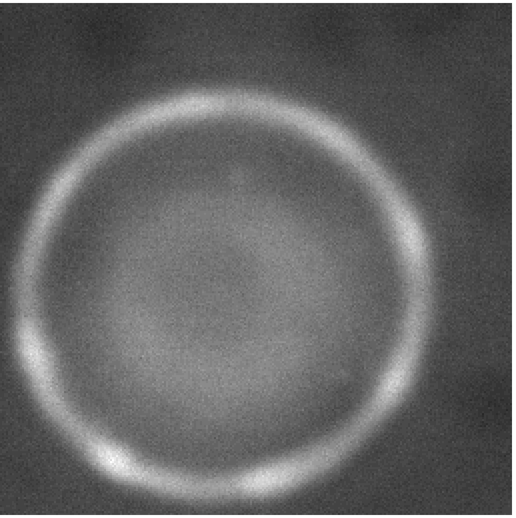


Test Campaign 1.5 (2018-2019)

- Additional 600 successful hot-fire tests
- Performance and operability examined for:
  - Variable throat size
  - Reduced annulus length
  - Variable reactant mixing (72->36 elements)
- Additional measurements implemented
  - Dynamic pressure transducers (plenums and annulus)
  - External microphones

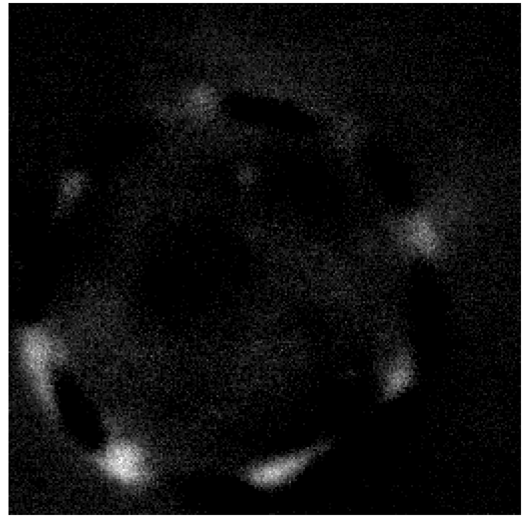
High-Speed Image Processing Technique

Raw Image



1

Corrected Image

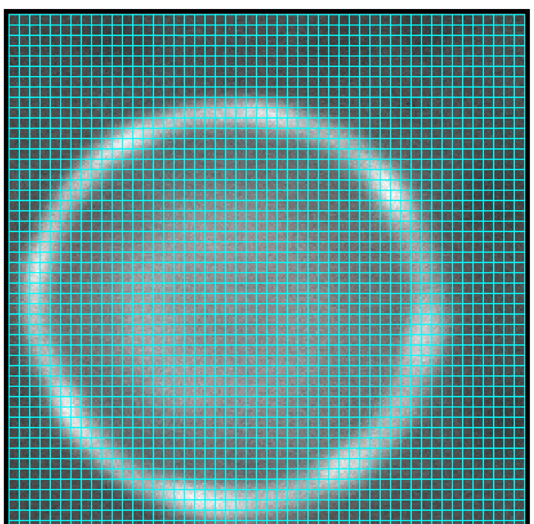


Processing Steps

1) Apply Background subtraction.
2) Segment image (256 X 256 resolution) into 50 X 50 squares.
3) Quantify $I_{pxl.}$ time trace for each box and find boxes with max. $I_{pxl.}$ amplitude. Fit circle to boxes using Taubin circle fit.
4) Segment circle into 200 angular divisions and again quantify $I_{pxl.}$. $I_{pxl.}$ is now fn(ɵ,t) as *r* dependence is removed.

2

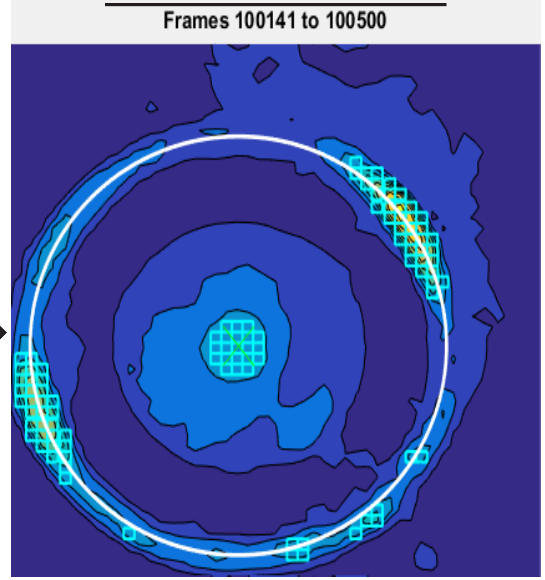
Cartesian Mesh



50x50 Grid

3

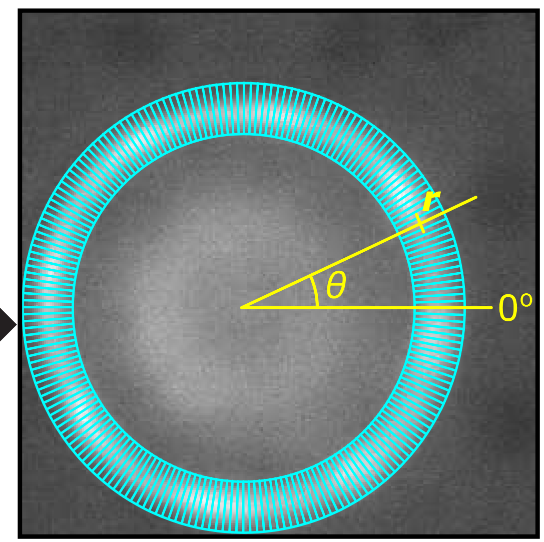
Annulus Location



Top 100 Boxes Considered

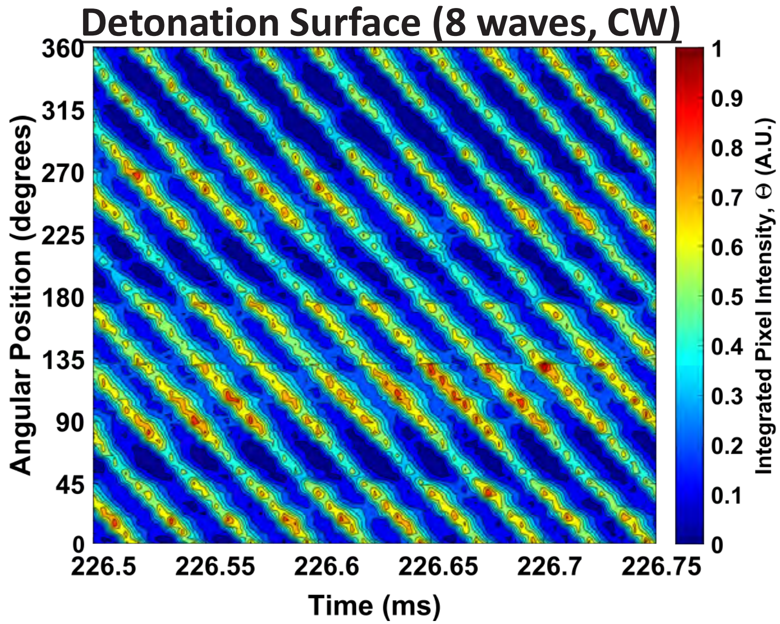
4

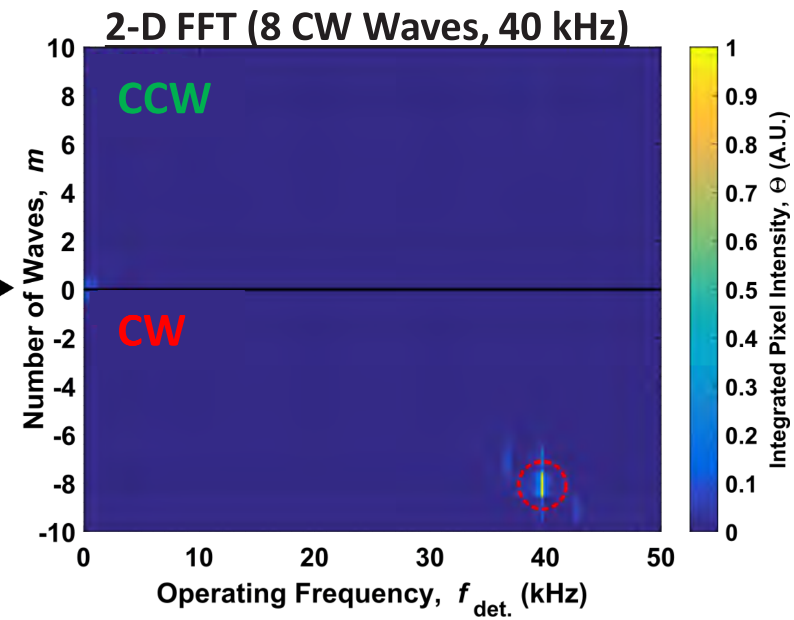
Polar Mesh

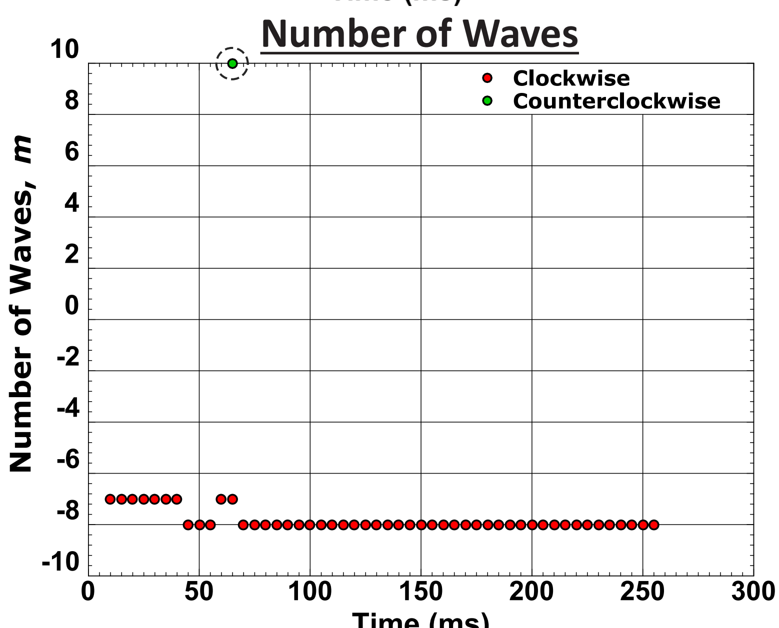


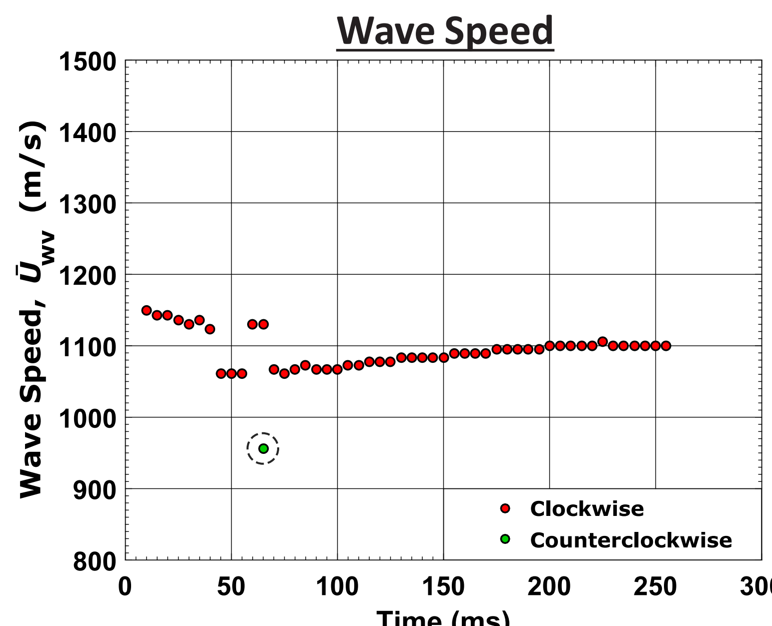
200 Angular Bins

Image Processing Results

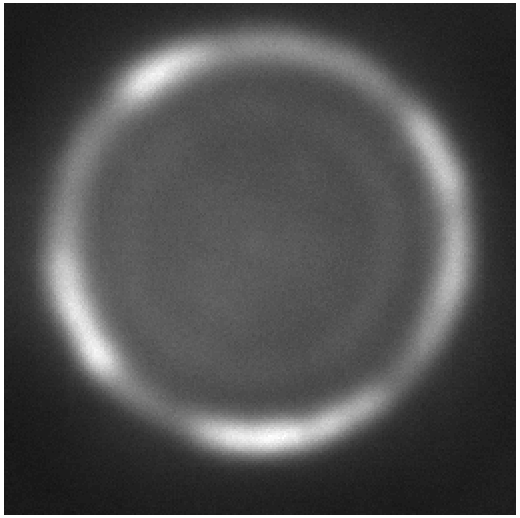


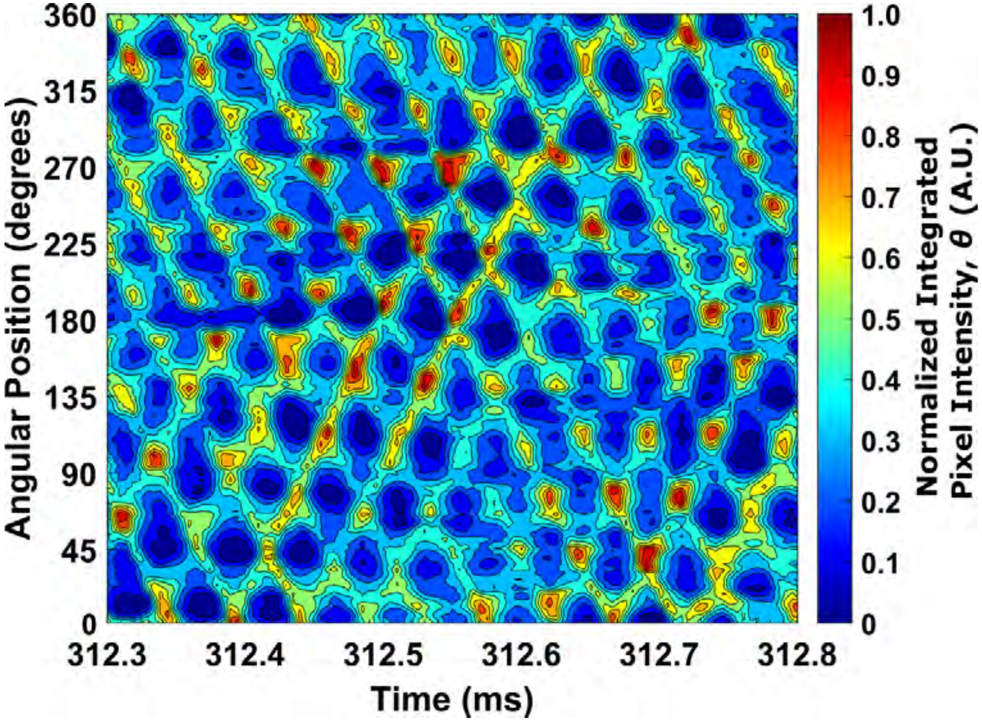






Counter-Propagating Modes

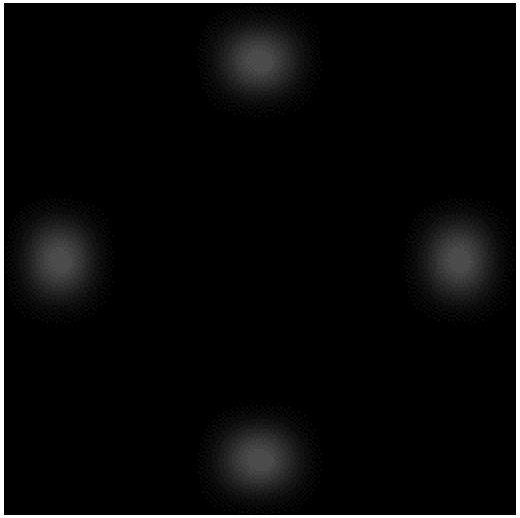




- Operating mode characterized by two sets of waves propagating in opposing directions
- Observed in low total mass flow and off-stoichiometric conditions
- Typically features a dominant (brighter) set of waves and an opposing (dimmer) set of waves
- Complex behavior makes even qualitative analysis difficult

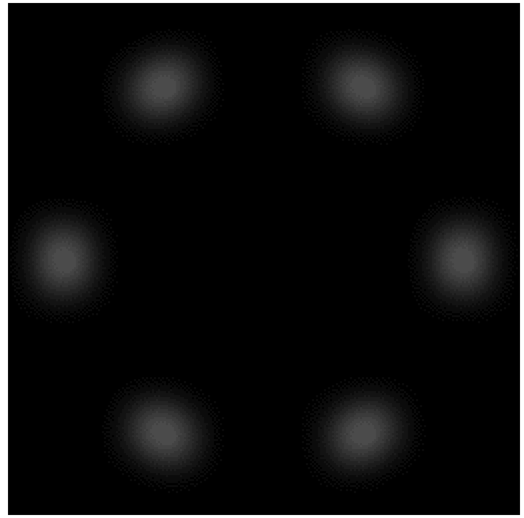
Counter-Propagating Mode Analysis: Synthetic Data

4 CCW Waves



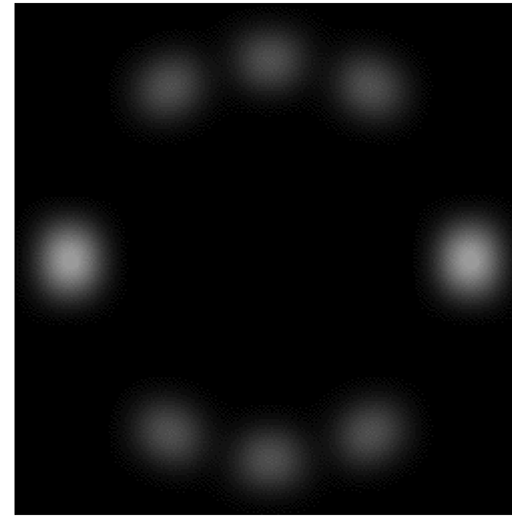
Number of Waves: 4
Orientation: CCW
$f_{det.}$: 35 kHz
$U_{wv.}$: 1955 m/s

6 CW Waves



Number of Waves: 6
Orientation: CW
$f_{det.}$: 40 kHz
$U_{wv.}$: 1490 m/s

Combined CP Mode



Number of Waves: 4/6
Orientation: CCW/CW
$f_{det.}$: 35/40 kHz
$U_{wv.}$: 1955/1490 m/s

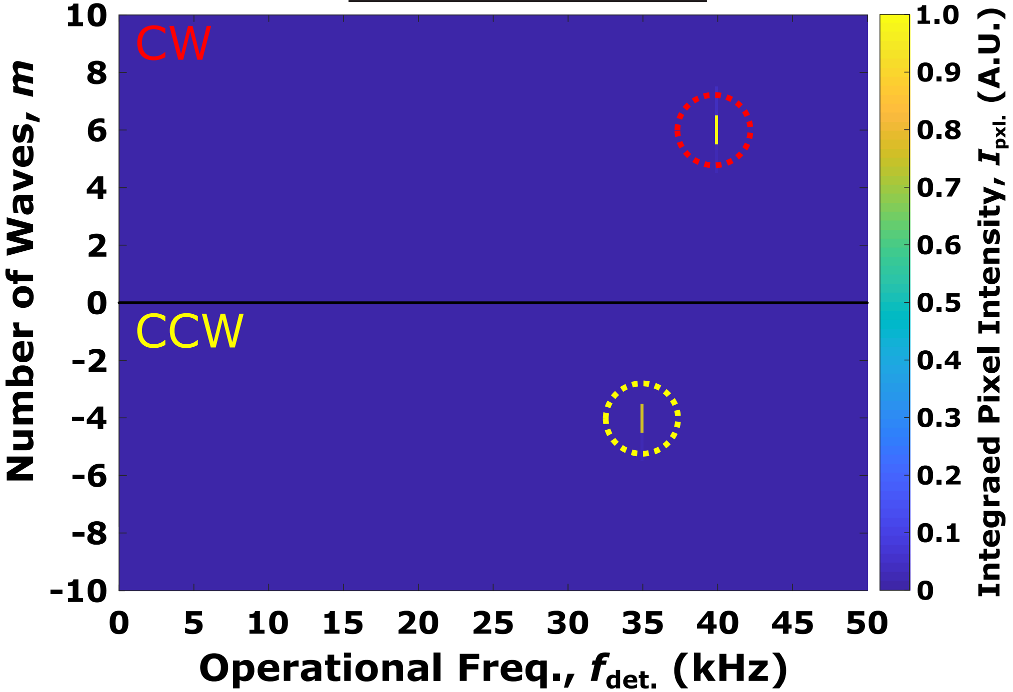
Motivation: Extract wave characteristics in both directions for the counter-propagating (CP) wave cases

- Sample test cases were generated with known wave parameters to send through the existing code to determine effects on automated analysis
- Synthetic data generated can alter number of waves, orientation, wave speed and luminescent intensity of detonation fronts.

AFRL

Counter-Propagating Mode Analysis

2-D FFT (Q1 & Q4)



Peak Frequencies

Number of Waves: +6 (CW)
$f_{det.}$: 40 kHz

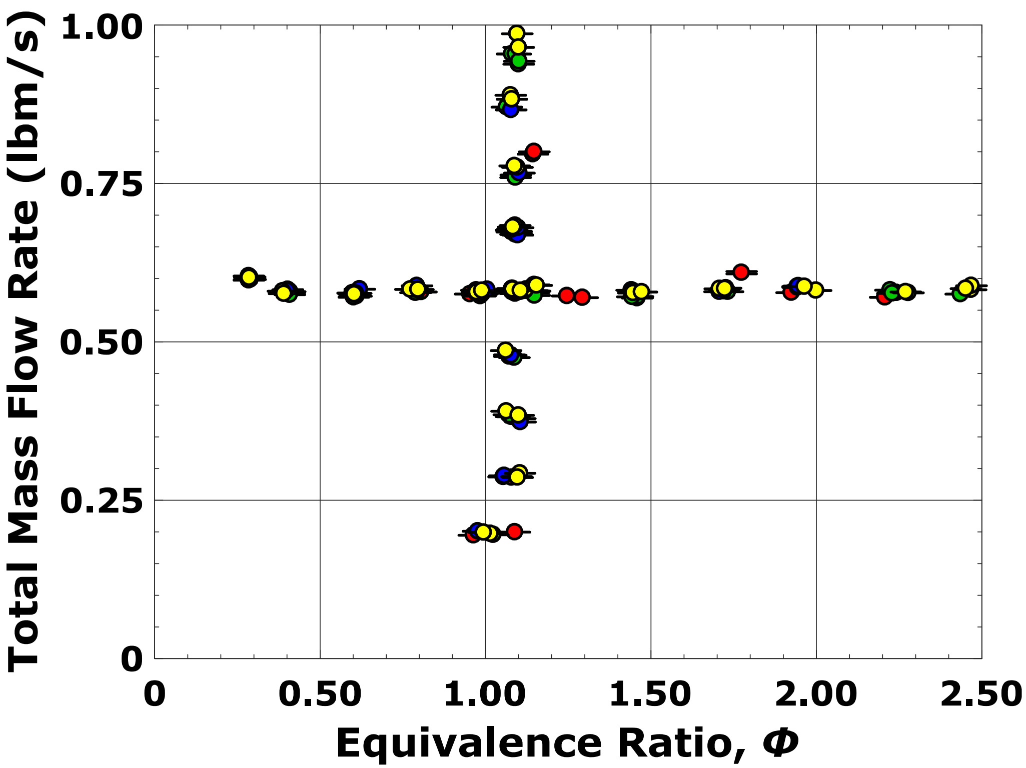
Number of Waves: -4 (CCW)
$f_{det.}$: 35 kHz

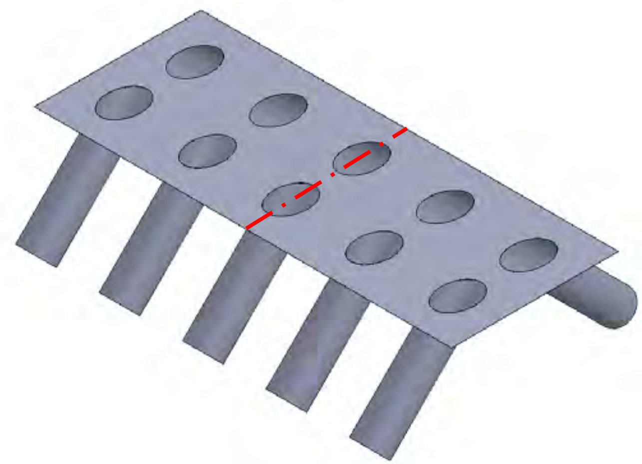
- **Dominant and opposing mode decoupled using 2-D FFT.**

- For more information about the image processing method and additional tools developed:
  - Bennewitz, J., Bigler, B., and Hargus,W., "Automated Image Processing Method to Quantify Rotating Detonation Wave Behavior," *Review of Scientific Instruments*, Submitted, Currently under review. 2019.

Injector Area Study - Flow Conditions

- Performed the following flow condition studies:
  - Equivalence Ratio Sensitivity: ϕ = 0.3 – 2.3, for $\dot{m}_{\text{tot}}$ = 0.6 lbm/s
  - Total Mass Flow Sensitivity: $\dot{m}_{\text{tot}}$ = 0.2 – 1.0 lbm/s, for ϕ = 1.1

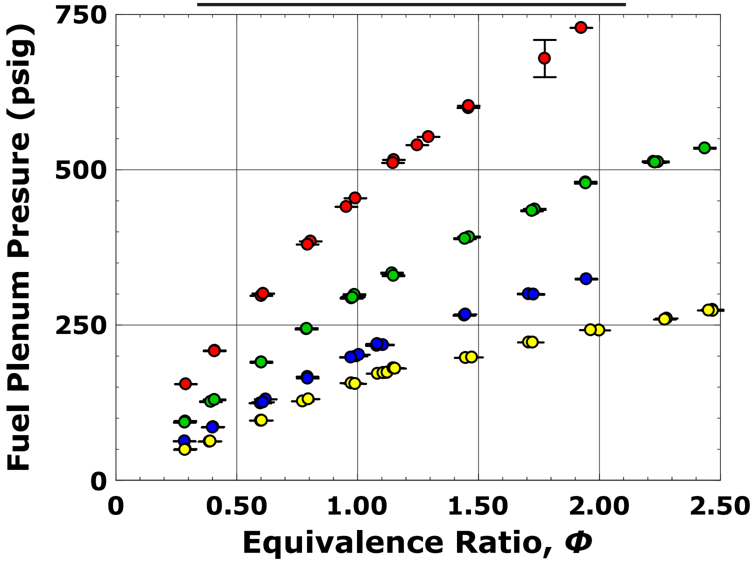




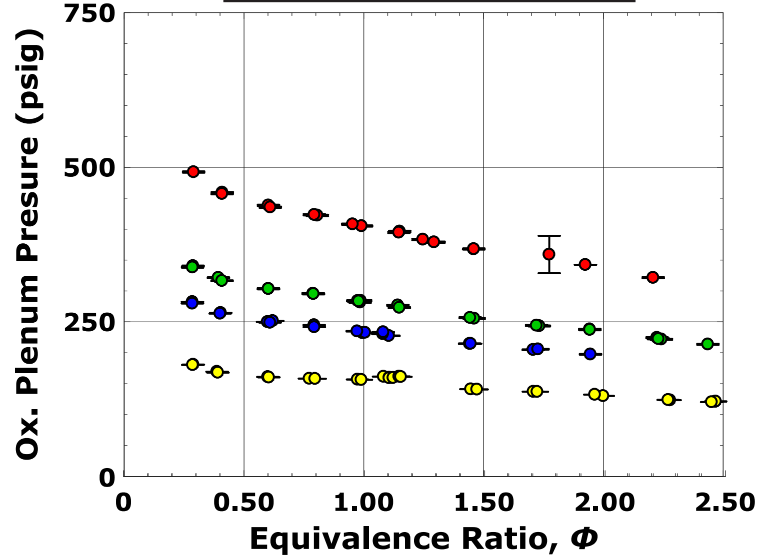
1.0A - Baseline
1.5A - 1.5X
2.0A - 2.0X
2.5A - 2.5X

Injector Area Study: Plenum Pressures

Fuel Plenum Pressure

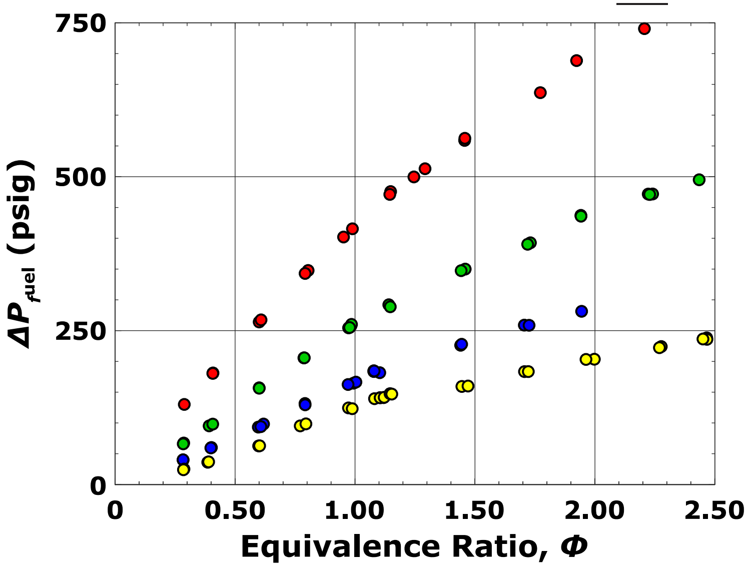


Ox. Plenum Pressure

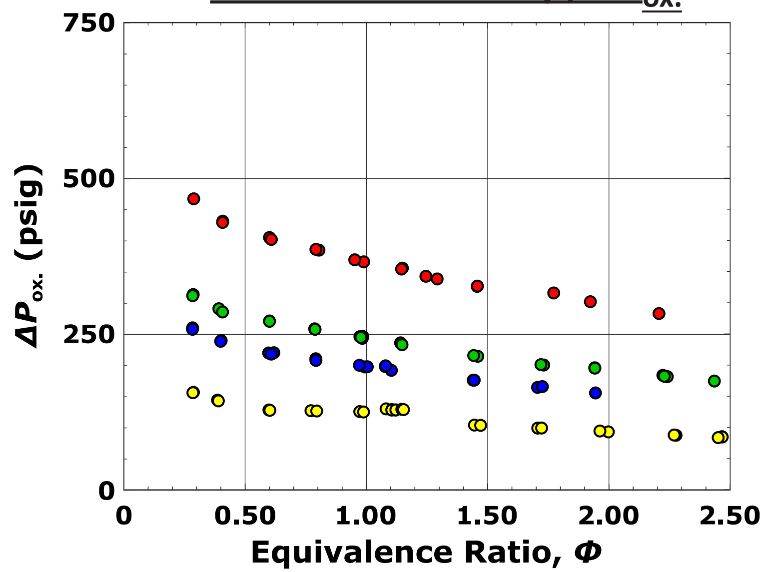


2.5A corresponds to a fuel pressure drop that is ~5X smaller than for 1.0A, while the ox. pressure drop is 3X smaller.

Fuel Pressure Drop, ΔP_{fuel}



Ox. Pressure Drop, $\Delta P_{ox.}$

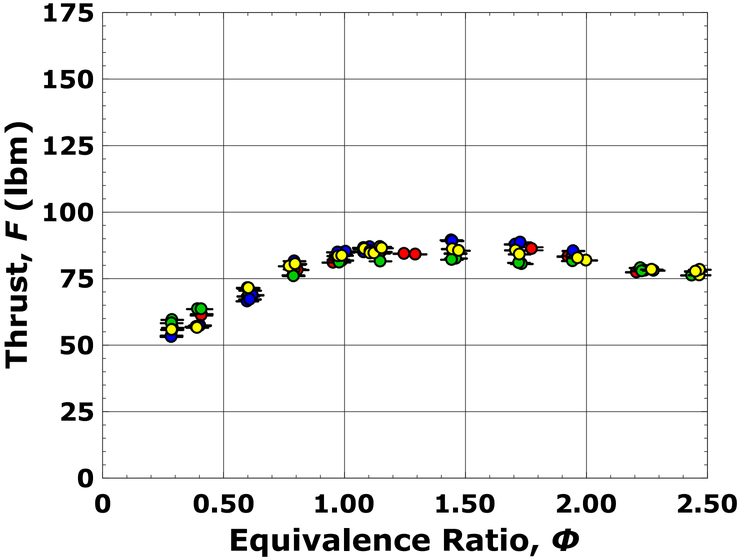


Sym. Legend

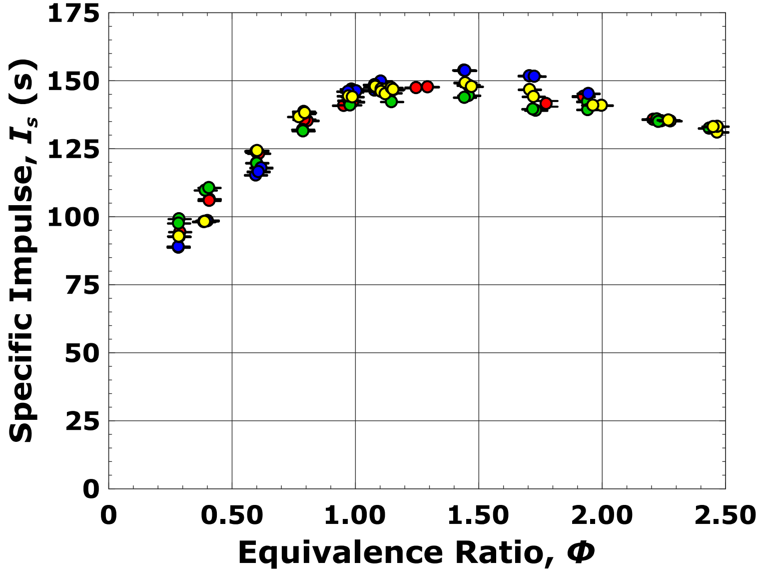
- 1.0A - Baseline
- 1.5A - 1.5X
- 2.0A - 2.0X
- 2.5A - 2.5X

Injector Area Study: Performance

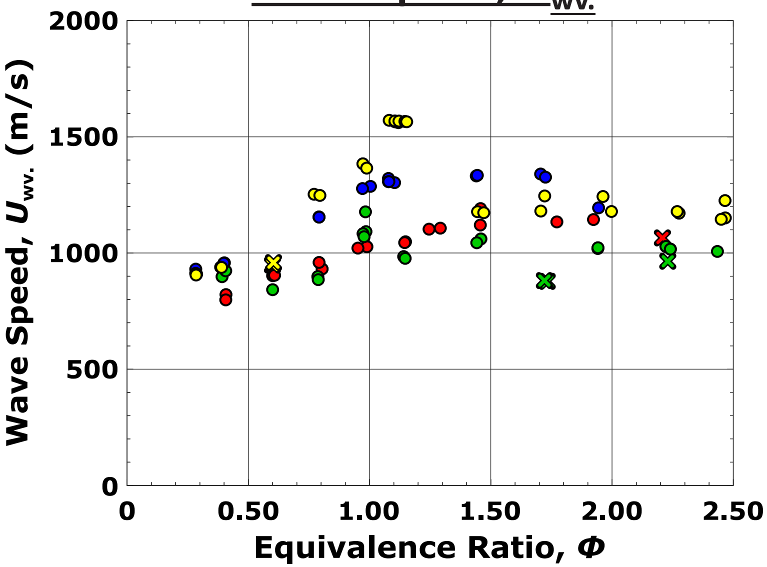
Thrust



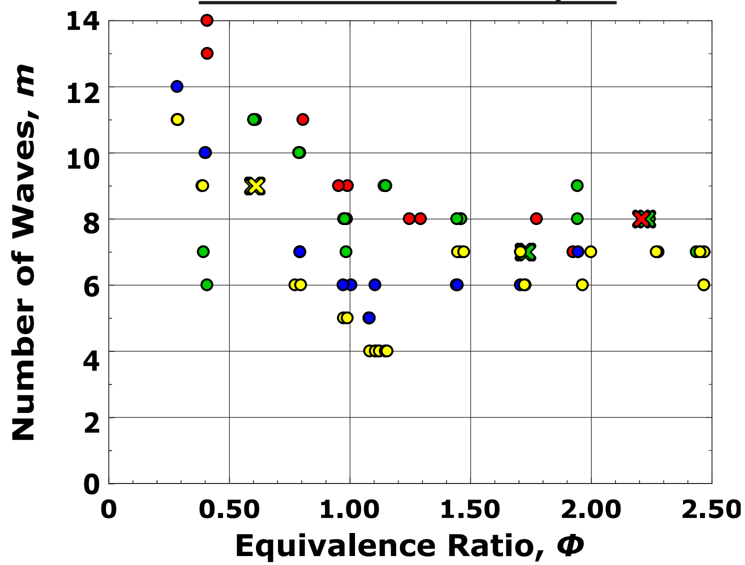
Isp



Wave Speed, $U_{wv.}$



Number of Waves, *m*

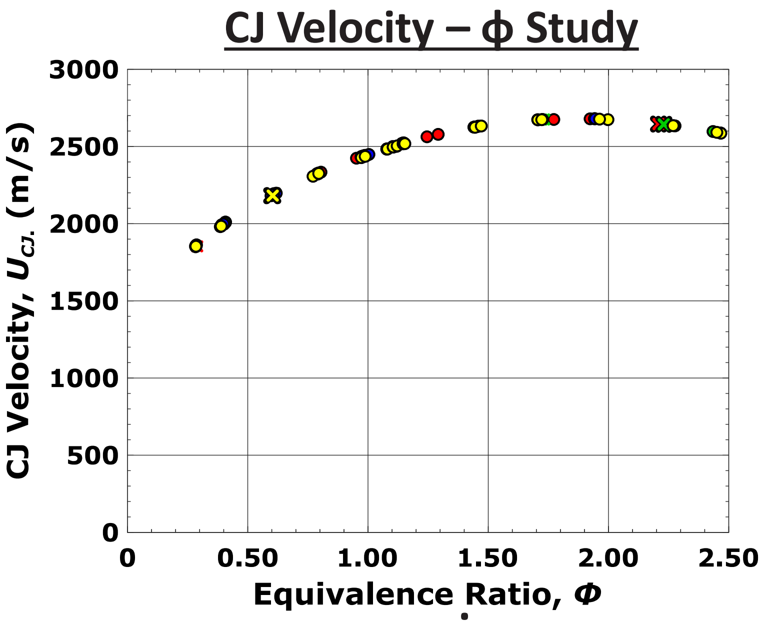


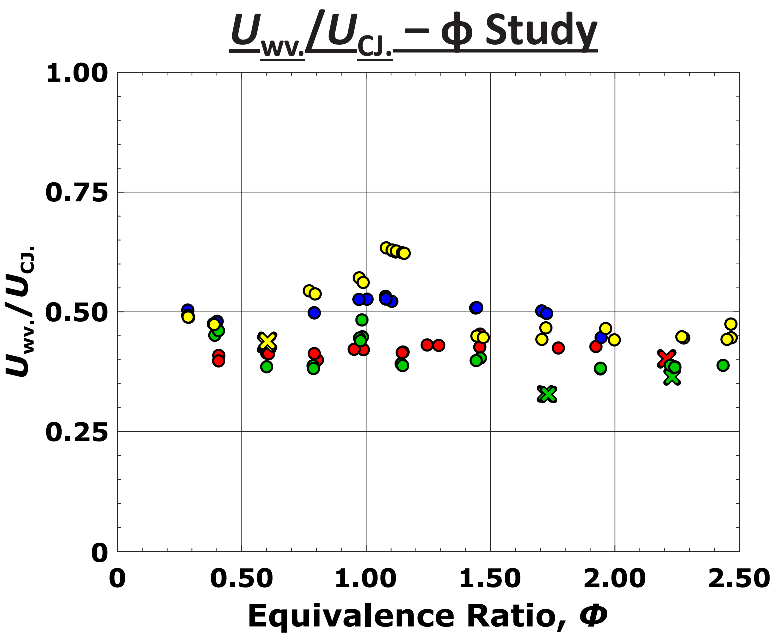
- Peak performance occurred at ϕ = 1.1 for all injector geometries, where I_s = 150 s.
- No appreciable change in performance observed for the various injector geometries.
- Max. performance appears to correlate with higher wave speeds.
- Counter-prop. occurs at off nominal conditions.
- Note: “X” denotes the existence of counter-propagating mode.

Sym. Legend

- 1.0A - Baseline
- 1.5A - 1.5X
- 2.0A - 2.0X
- 2.5A - 2.5X

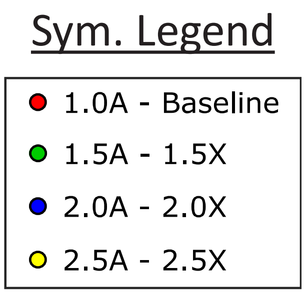
Injector Area Study: CJ Vel.





- Chapman-Jouguet velocity was calculated using NASA CEA as a fn(φ, T = 298 K and P = CTAP1).

- $U_{wv.}/U_{CJ.}$ ranged from 33-71%



Injector Area Study: Concluding Remarks

- Demonstrated operability of RDRE from ϕ = 0.25 to 2.5, where peak performance of F = 90 lbf and I_s = 150 s occurred at ϕ = 1.1.

- **While increasing the injector hole size from 1.0A to 2.5A decreased the injector pressure drop. 3-5X, there was no appreciable change in performance or operability.**

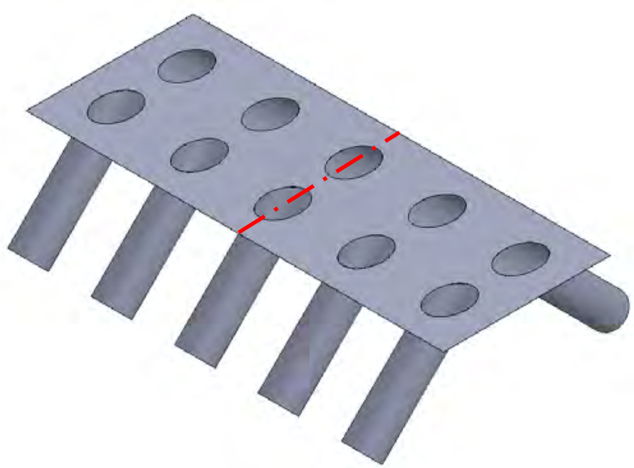
- $U_{wv.}/U_{CJ.}$ ranged from 33-71% for the various flow conditions and injector geometries, where wave speeds were generally higher at max. Isp.

- For more information:
  - Bennewitz, J., Bigler, B., Hargus, W., Danczyk, S., and Smith, R., "Characterization of Detonation Wave Propagation in a Rotating Detonation Rocket Engine using Direct High-Speed Imaging," 54th *AIAA Joint Propulsion Conference*, 2018.

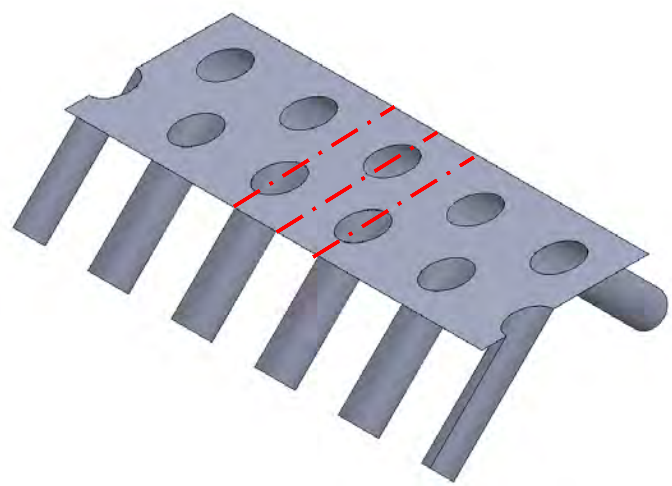
Injector Alignment Study

- Objectives and Motivation:
  - Demonstrate operation of gas-gas RDRE with two different injector geometries
  - Determine effects on operability limits, performance and detonation mode characteristics for aligned and misaligned injectors
  - Evaluate importance of injection schemes in gas-gas studies

Aligned

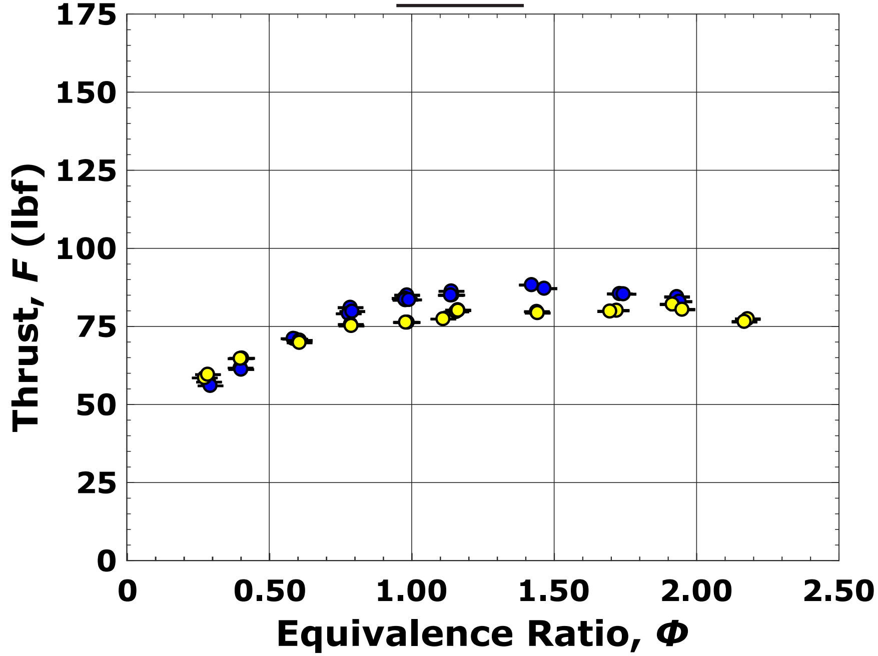


Misaligned

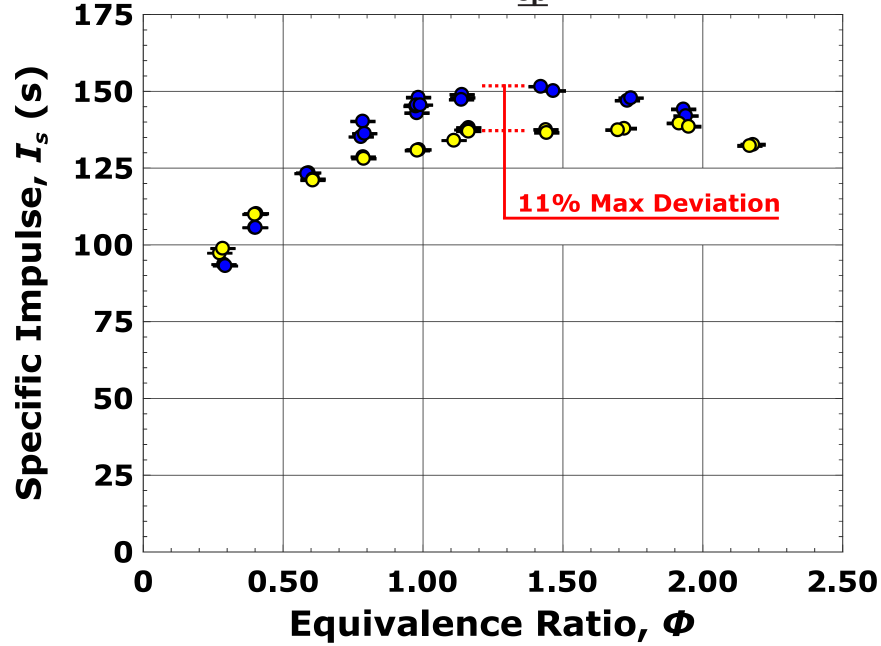


AFRL Injector Alignment Study: Performance Trends

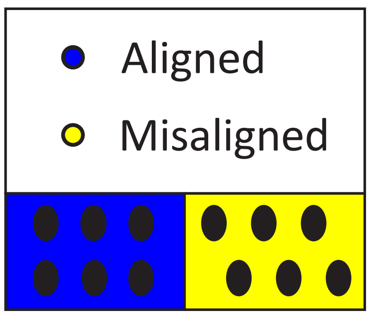
Thrust



I_{sp}

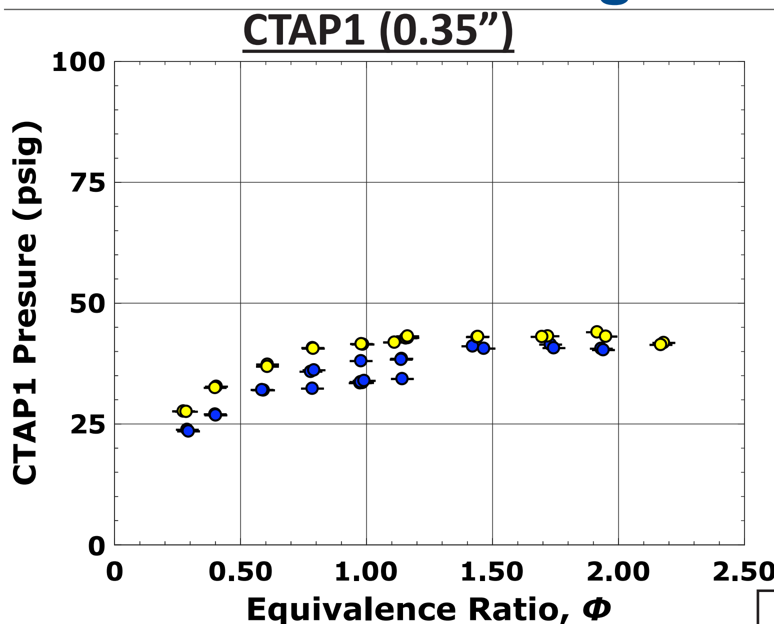


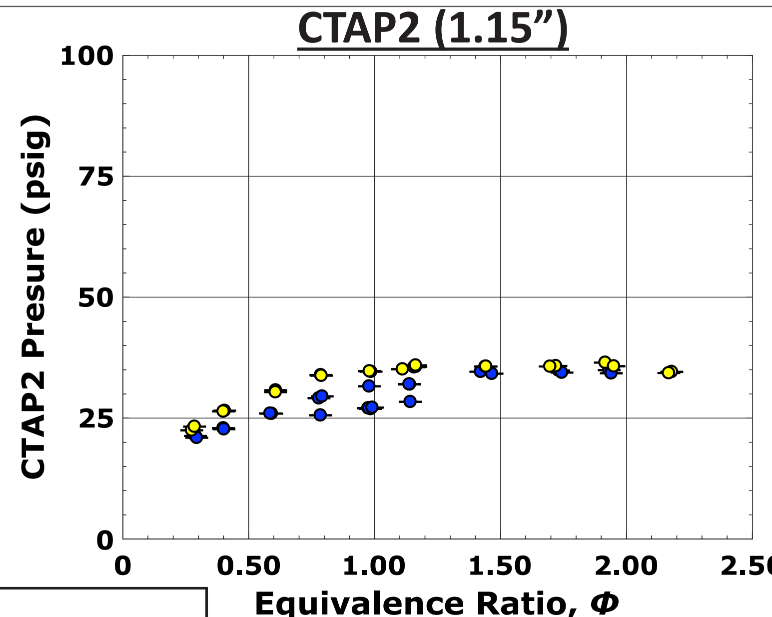
Sym. Legend

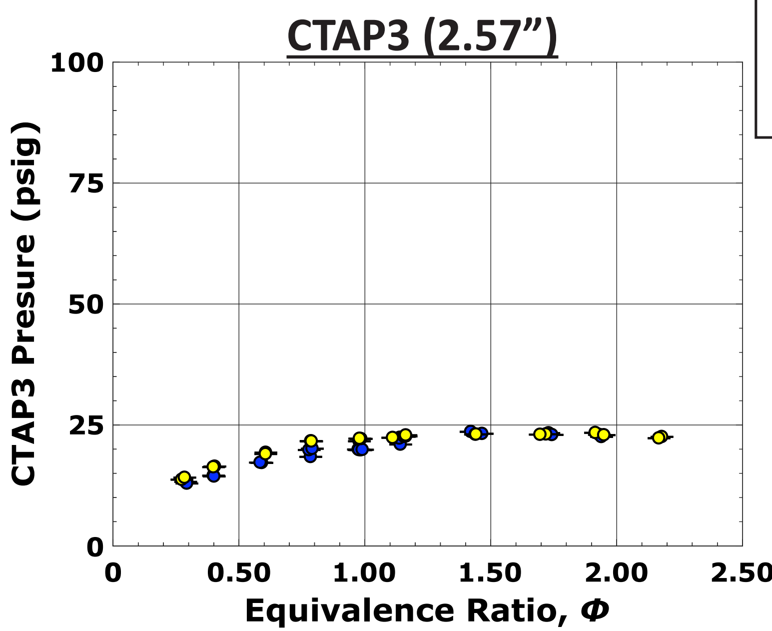


- 11% Max. deviation between the two injector configurations at peak performance ($\phi = 1.1$).
- Minimal deviation for fuel-rich and fuel-lean conditions
- Operability range was not changed by altering injector configuration.

Average Chamber Pressure

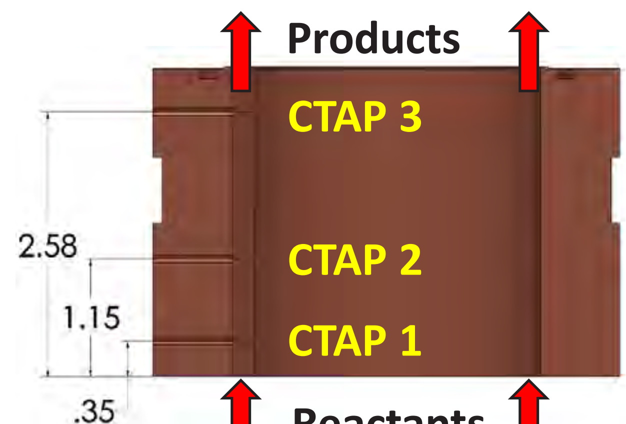




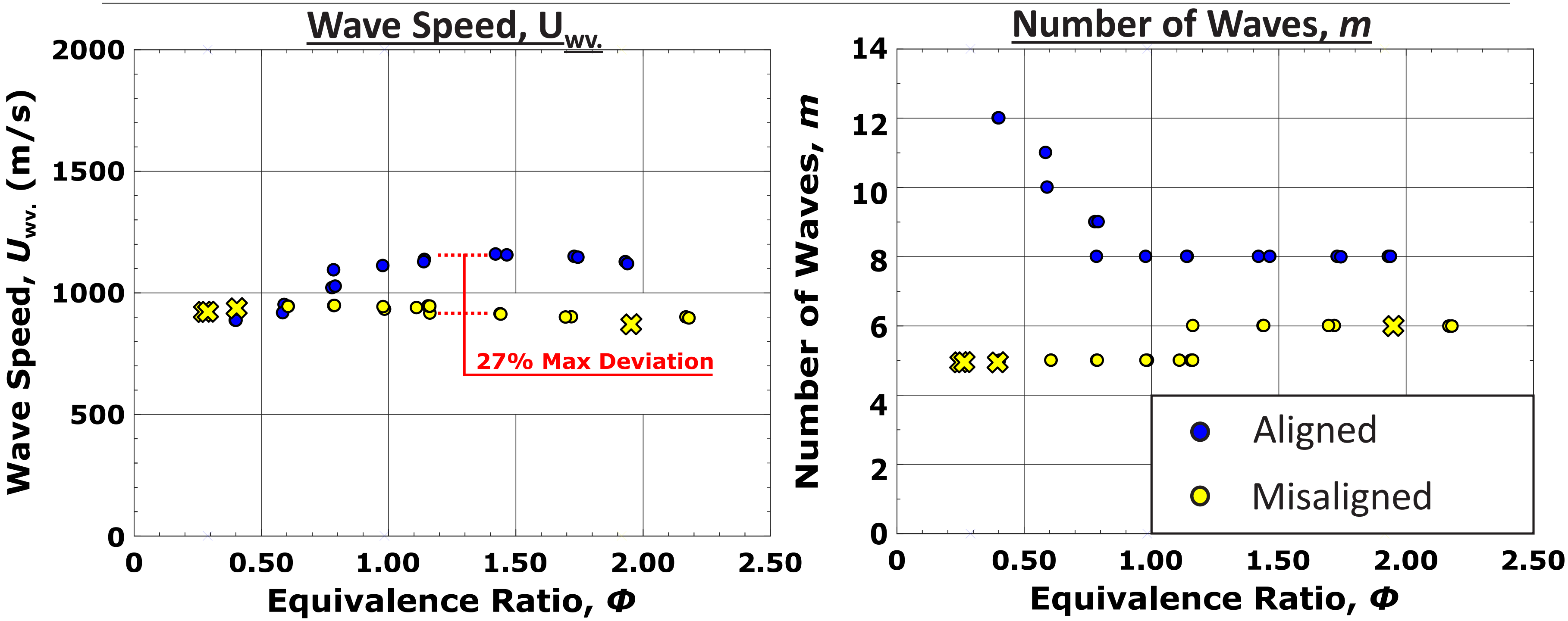


- Aligned
- Misaligned

Detonation zone pushed downstream for misaligned configuration



Wave Propagation Characteristics



- Max. wave speed deviation occurs at peak performance ($\phi = 1.1$) and fuel rich conditions.
- Fewer waves with misaligned injectors
- Counter-prop. occurs at off nominal conditions and more prevalent for the misaligned config.

Note: "X" denotes the existence of counter-propagating mode.

For misaligned tests, wave speed is insensitive to flow condition

Injector Alignment: Concluding Remarks

- Alignment of injectors had no effect on operability limits
- Misaligned injectors showed decrease in performance near ϕ=1
  - 11% maximum decrease in Isp
  - 27% maximum decrease in wave speed
  - **Wave speed insensitive to flow condition**
- **Increased pressure in CTAP 1 and 2 for misaligned configuration**
  - Detonation zone moved downstream
  - Exception to general CTAP/performance trend
- For more information:
  - Bigler, B., Bennewitz, J., Schumaker, S., Danczyk, S., and Hargus, W., "Injector Alignment Study for Variable Mixing in Rotating Detonation Rocket Engines," *AIAA SciTech Forum*, 2019.

Unsteady Wave Behavior

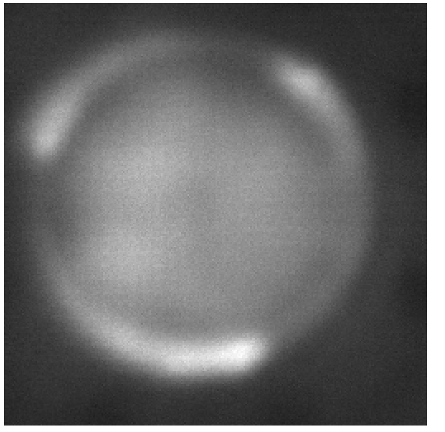
Background

- Steady operating mode corresponds with constant angular separation
- Mode transitions observed for a variety of flow conditions
- Unsteady behavior can lead to unexpected engine operation

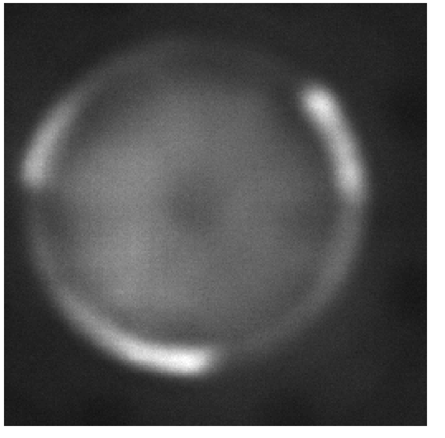
Objectives

- Characterize transition behavior
- Quantify time scales of transition periods for ascending and descending transitions
- Examine stability of a given mode by tracking the relative locations and velocities of each wave front

Steady Operating Mode

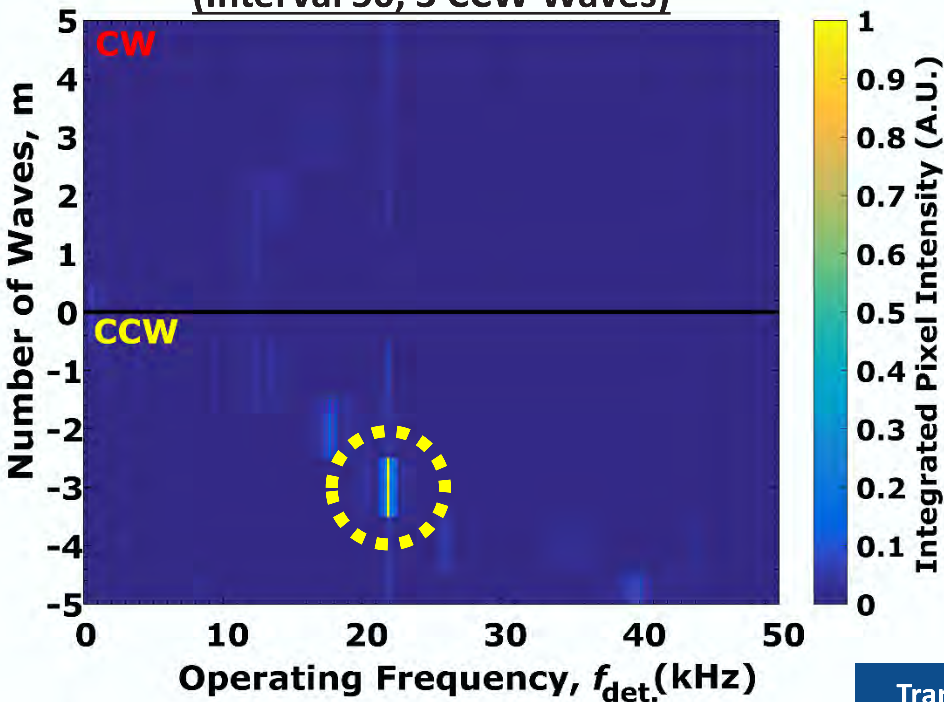


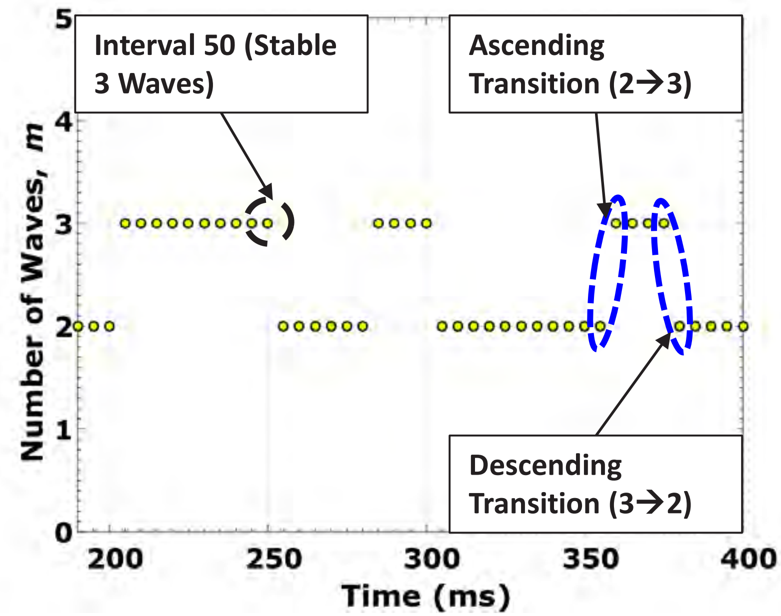
Unsteady Transition



Average Modal Properties

Example 2-D FFT of Det. Surface
(Interval 50, 3 CCW Waves)





Transition Type	Mode	Start Time (ms)	Duration (ms)
Ascending	2 → 3	201 282 357	1.46 1.37 1.76
Descending	3 → 2	250 300 **370**	3.54 1.35 **3.08**

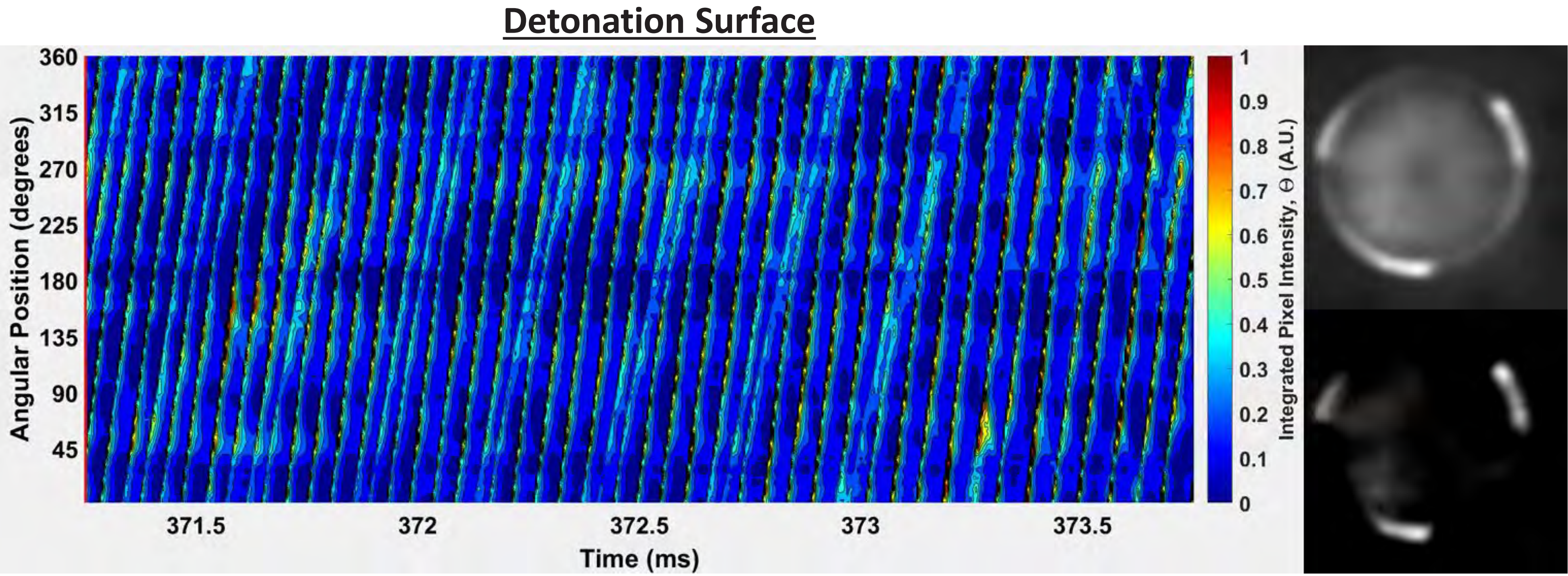
Max. Peak Characteristics

Num. Waves: $m = 3$

Operational Frequency: $f_{det.} = 22.0$ kHz

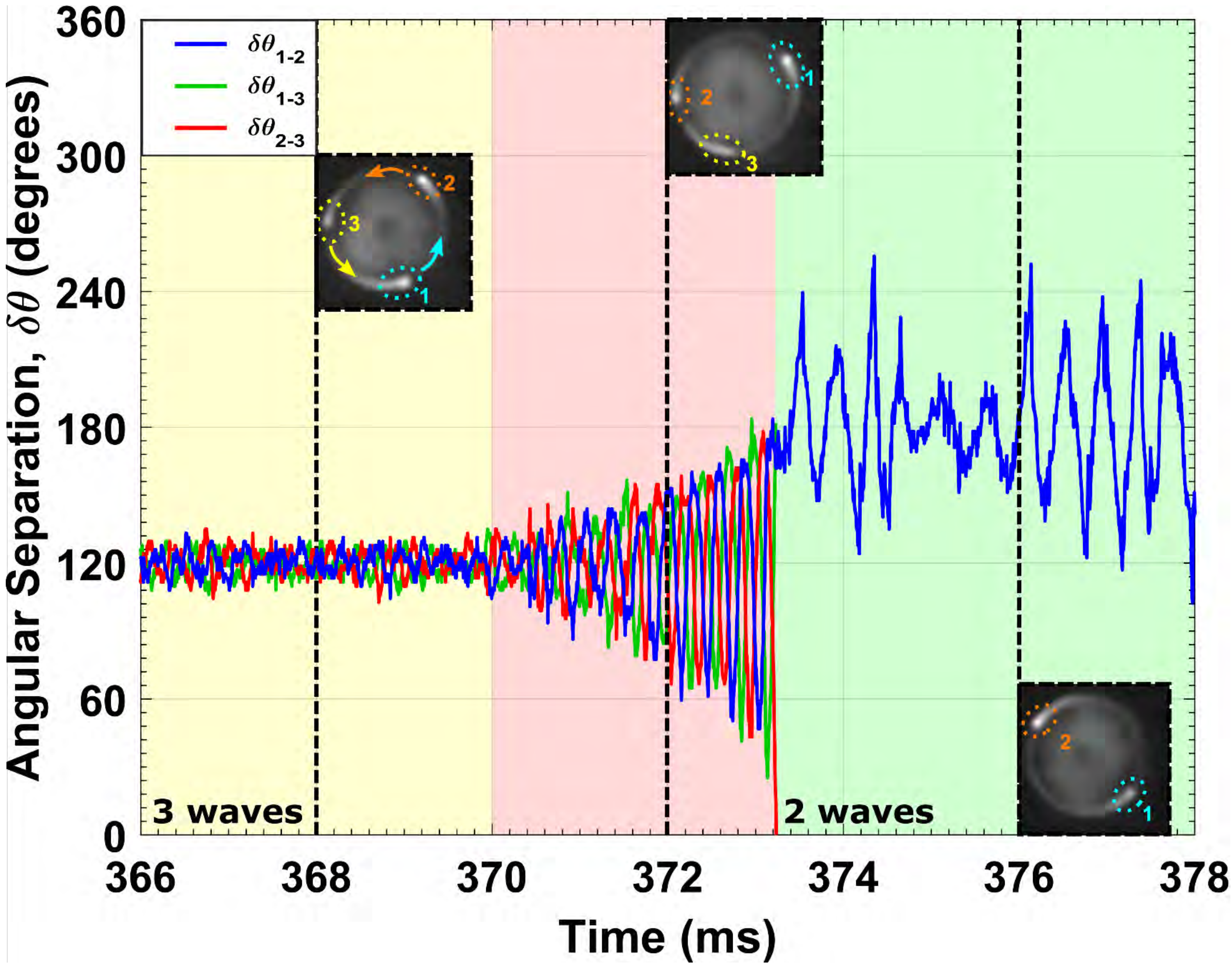
Det. Wave Speed: $U_{wv.} = 1638.5 \frac{m}{s}$

Descending Transition (3 → 2)

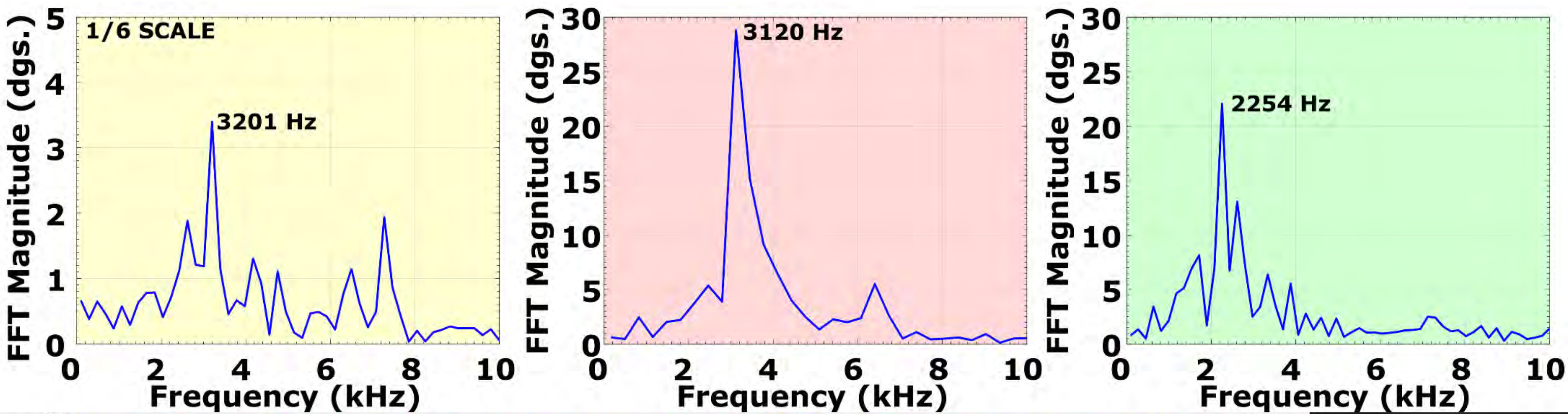


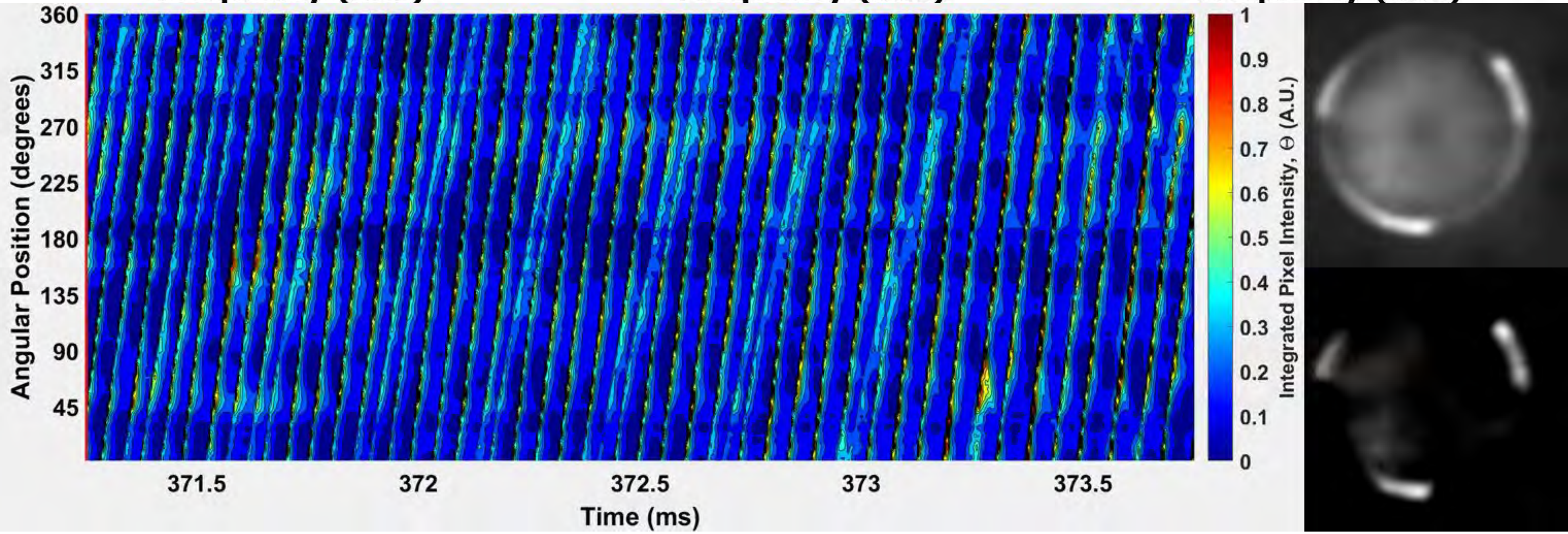
- A transition event occurs from 3 CCW waves to 2 CCW.
- Non-uniform spacing among the waves appears due to “galloping-type” detonation behavior at the onset of transition (Wolanski, 2011).
- Eventually, one wave gets consumed by another that overtakes it during momentary acceleration event.

3→2 Transition Angular Separation

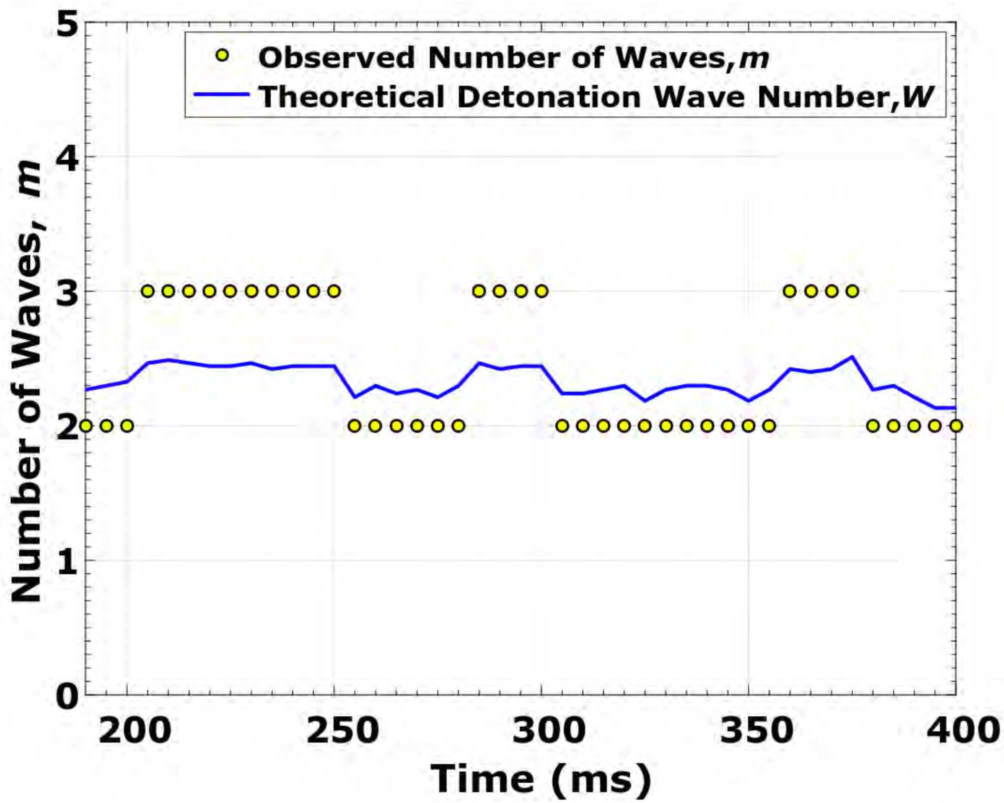


3→2 Transition Frequency Spectra





RDE Mode Stability Criterion



- Relates the available reactant fill volume to a critical number of waves
- Theoretical number of waves between integer values correspond with galloping behavior

Mode Transitions: Concluding Remarks

- Image processing tools extended to track the instantaneous angular position of each wave
- For these test conditions, 3 waves are more stable than 2 waves:
  - Descending (3→2)
    - 3 waves: $\delta\theta' = 4°$ $U'_{\text{wv.}}/\overline{U}_{\text{wv.}} = 1\%$
    - 2 waves: $\delta\theta' = 22°$ $U'_{\text{wv.}}/\overline{U}_{\text{wv.}} = 5\%$
    - Transition: $\delta\theta' = 157°$ $U'_{\text{wv.}}/\overline{U}_{\text{wv.}} = 28\%$
- Galloping-type behavior associated with transitions
- Descending transitions preceded by increasing galloping behavior leading to consumption of one wave
- Also examined ascending transition (2→3) and direction reversal (CCW→CW)
    - Bennewitz, J., Bigler, B., Pilgram, J., and Hargus,W., "Modal Transitions in Rotating Detonation Rocket Engines," *International Journal of Energetic Materials and Chemical Propulsion*, Accepted. Awaiting publication, 2018.

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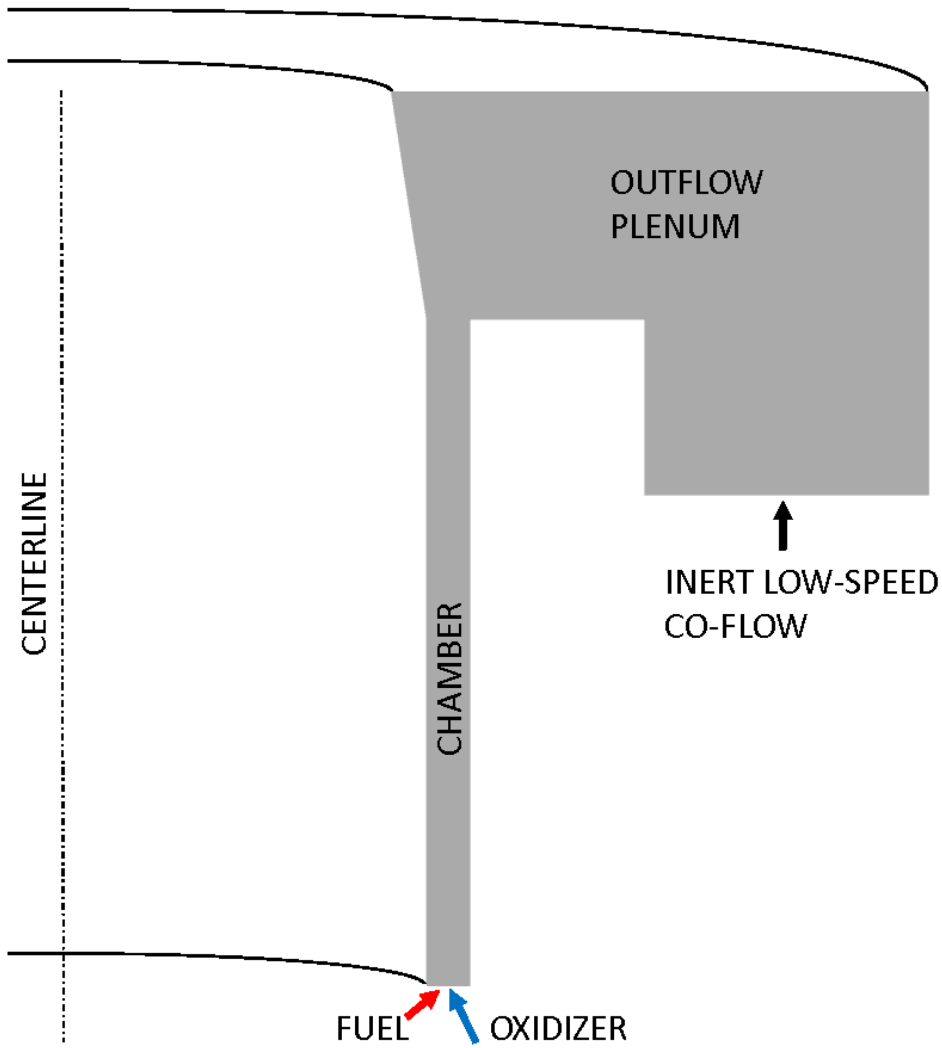
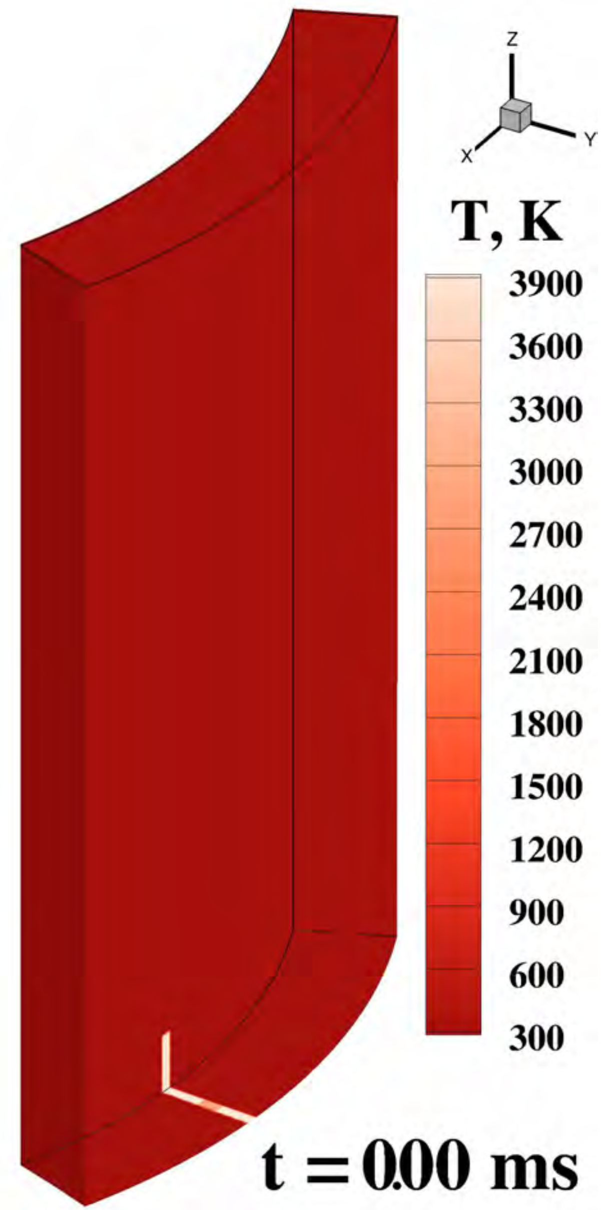
Partial Annulus Simulation

- Only **1/8th annulus sector** used, i.e. assume 8 total waves per experiment
    - Injectors and inflow plenums
    - Chamber
    - Large outflow plenum
- Block-structured LES code AHFM
    - 2nd order in time/space
    - MUSCL upwind
- Modified 6 species/5 step Westbrook-Dryer mechanism
- Approximately 10M cells, using 0.18M CPU-hours in total



Partial Annulus Simulations

- LESLIE (LES with LInear Eddy model)
  - 2nd order in time and space
  - Full reactive NS with transported k
  - Westbrook-Dryer (6 species) chemistry
- Cases
  - 104 (base) with 8 injector pairs
  - 119 (rich) with 9 injector pairs
- Flowfield evolution
  - Ignition kernel burns initial field and creates shocks (t = 0.0 ms)
  - Shocks weaken and reactants are replenished (t = 0.1 ms)
  - Two counter-propagating shocks are set up in each direction (t = 0.4 ms)
  - Three of the waves die out, leaving a single detonation (t = 0.7 ms)



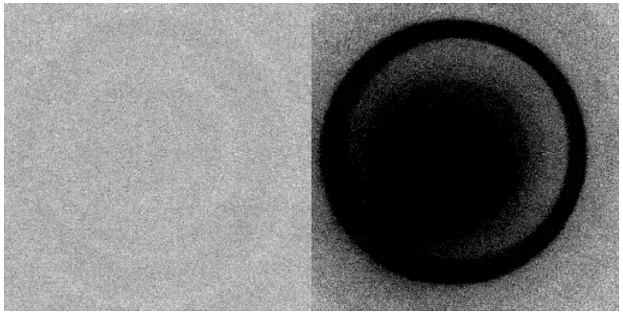
Notable Observations: Captured Startup Sequence

- Startup process follows:
  (1) Two detonation waves originate at pre-det location and consume one another (0.1 ms)
  (2) Momentary pause in visible wave propagation (0.2 ms) before counter-propagating behavior commences
  (3) Counter-propagating mode propagates with higher number of waves than stable condition (0.6 ms)
  (4) Single set of waves at higher number dominates for some time (0.8 ms)
  (5) Stable behavior at lower number of waves

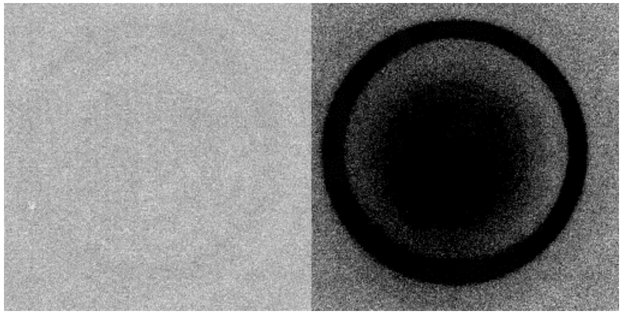
- Both tests reach stable conditions by 2.5 ms.

- **Transient behavior at startup is qualitatively consistent with simulations**

Test 763, ϕ = 1.15: 4 Stable Waves



Test 764, ϕ = 0.79: 5 Stable Waves



Case Descriptions

	104 (Base)	119 (Richer mixture)	124 (Higher mass flow)
$\dot{m}$ (kg/s)	0.263	0.276	0.363
Φ	1.15	1.77	1.15
p_{fuel} (MPa)	3.58	4.66	4.49
p_{oxid} (MPa)	2.75	2.58	3.65
T_{in} (K)	300	300	300
Number of Waves	9	8	10

Experimental Comparison

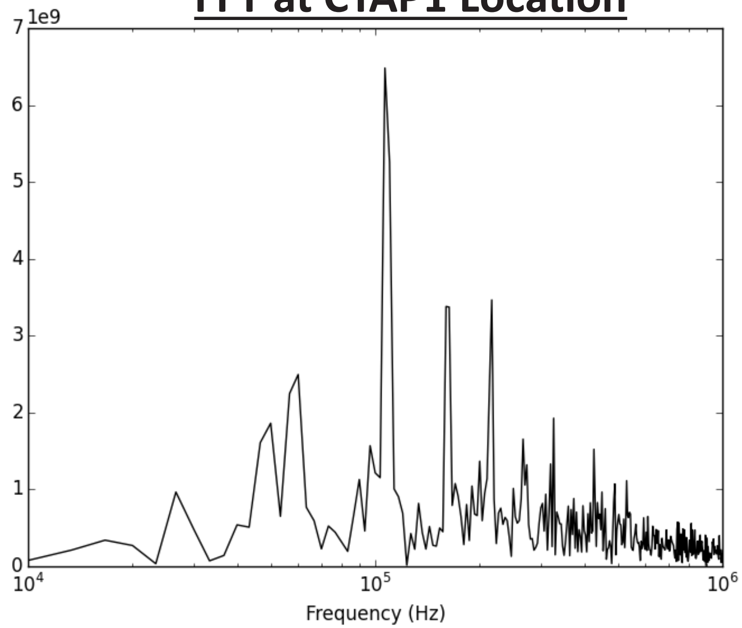
- CASE 104 (BASE)

	Experiment	Simulation
CTAP (psia)	53.9	52.7
Wave speed (m/s)	1050	1320, 1490
Refresh time (μs)	23.7	18.8, 16.7
Thrust (lbf)	85.0	105.8

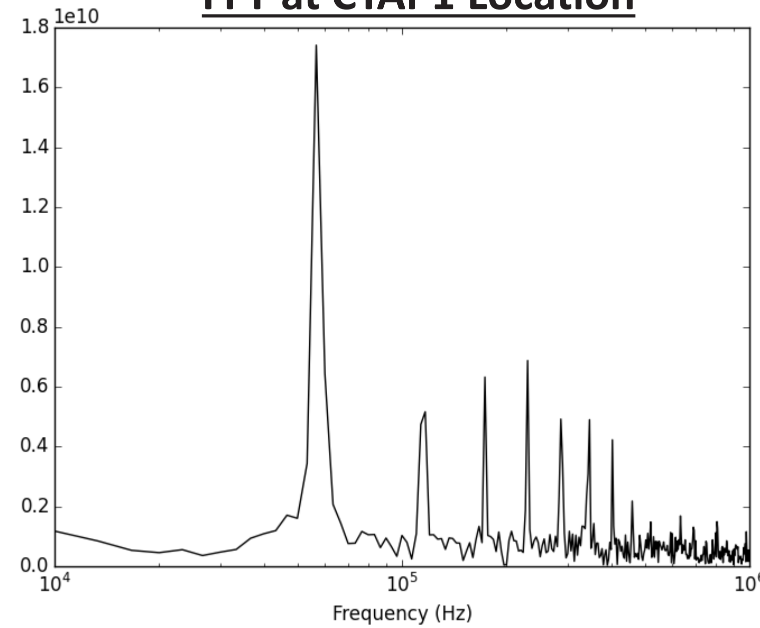
- CASE 119 (RICH)

	Experiment	Simulation
CTAP (psia)	56.5	64.2
Wave speed (m/s)	1130	1580.0
Refresh time (μs)	24.7	17.6
Thrust (lbf)	86.0	127.5

FFT at CTAP1 Location

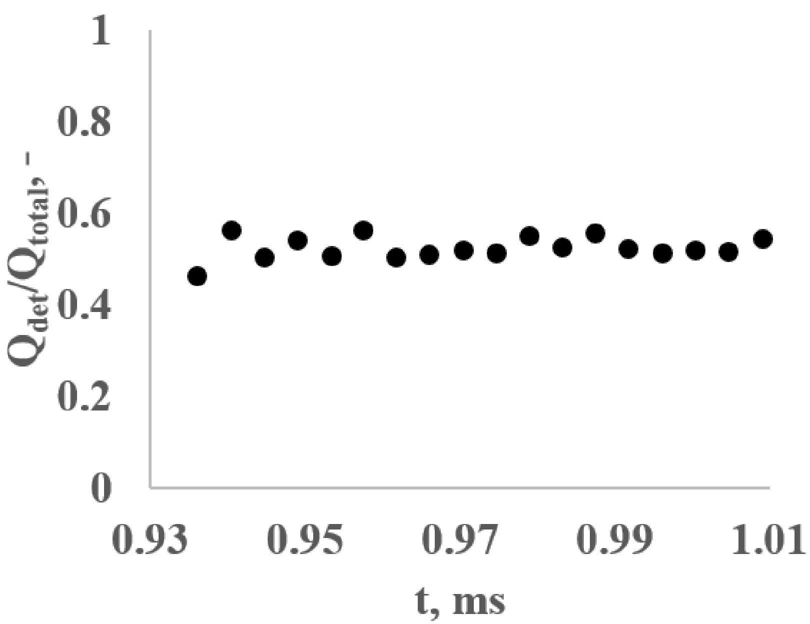


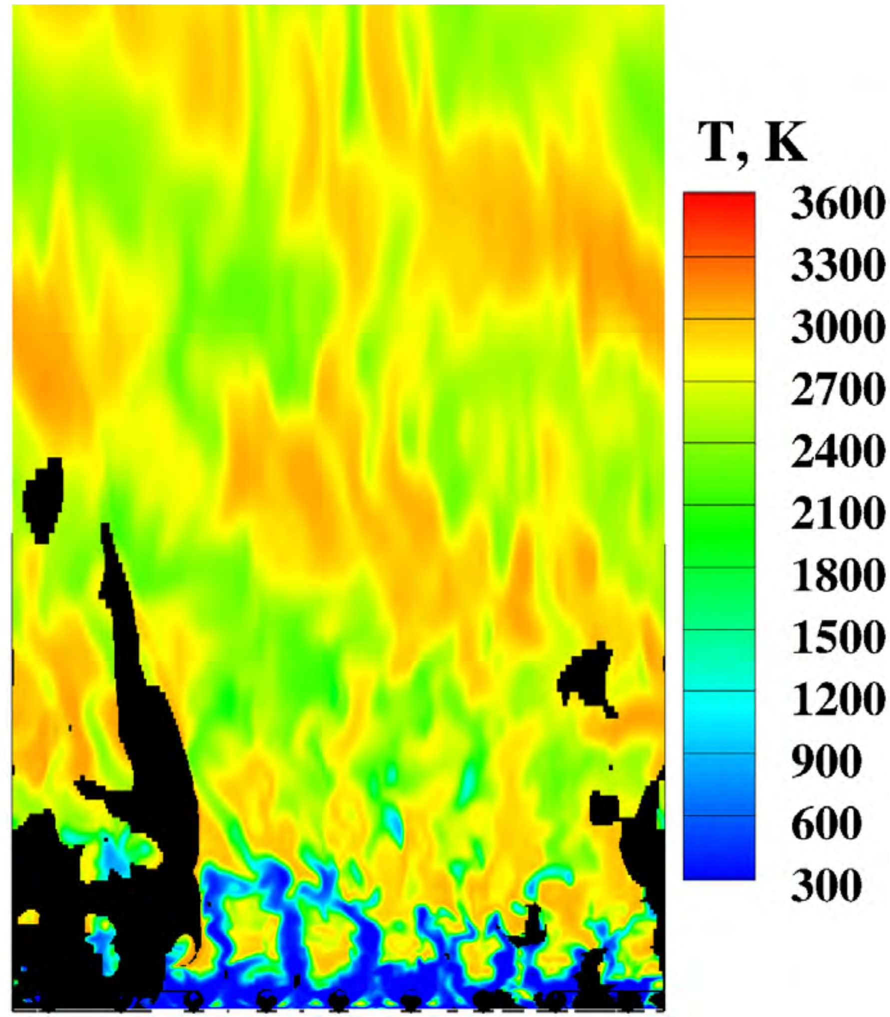
FFT at CTAP1 Location



Global Heat Release

- Detonation and deflagration delineated using 5 atm isocontour
- Heat releases calculate using mass-weighted volume integration
- Plot below indicates that even by conservative definitions, only half of the reactants detonate





Partial Annulus Simulations: Concluding Remarks

- Start-up transient behavior is qualitatively similar to experiment, starting from many waves and diminishing toward a quasi-steady state periodicity
- Non-premixed wave speeds significantly slower than pre-mixed simulations (~60% of CJ)
- Wave speeds consistently several hundred m/s faster than experiment
  - WD chemistry model yields fast detonation, regardless of premixedness
  - unmodelled heat loss expected to further impact speed

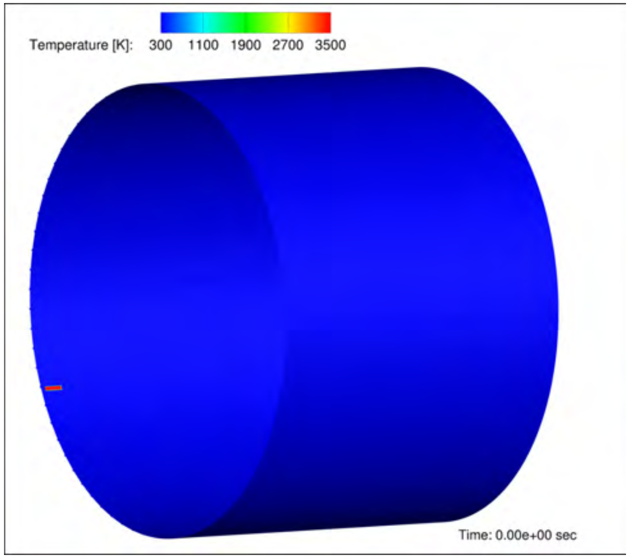
- Imposing number of waves may be responsible for deviations in performance, wave speed

Full annulus simulations

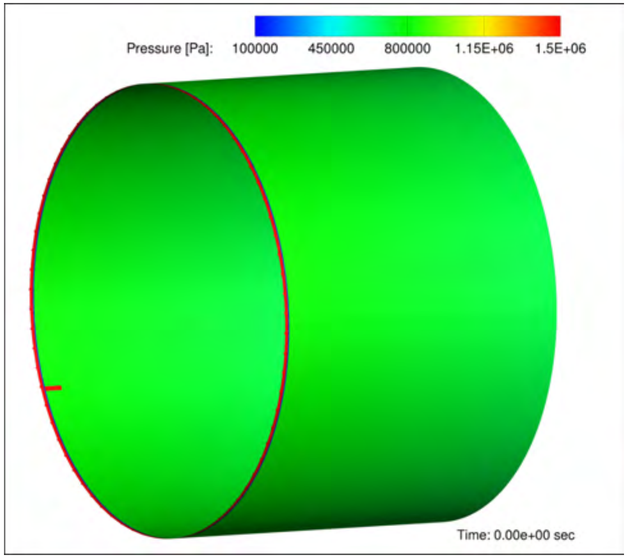
- LESLIE (LES with LInear Eddy model)
  - 2nd order in time and space
  - Full reactive NS with transported k
  - Westbrook-Dryer (6 species) chemistry
- Cases
  - 104 (base) with 72 injector pairs
  - 124 (high $\dot{m}$) with 72 injector pairs
- Flowfield evolution
  - Ignition kernel burns initial field and creates shocks (t = 0.0 ms)
  - Shocks weaken and reactants are replenished (t = 0.1 ms)
  - Over 20 shocks travel around the annulus, irregularly spaced (t = 0.3 ms)
  - Most waves die out, eventually settling on 8 detonations (t = 0.8 ms)

8 waves naturally excited during steady-state (number of waves not imposed)

Temperature

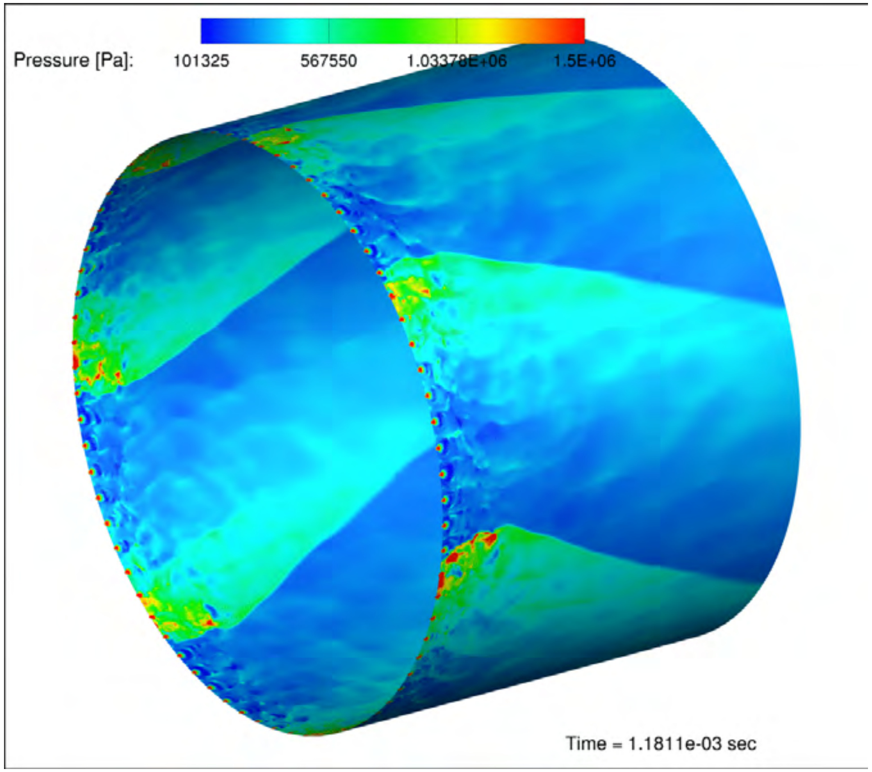


Pressure

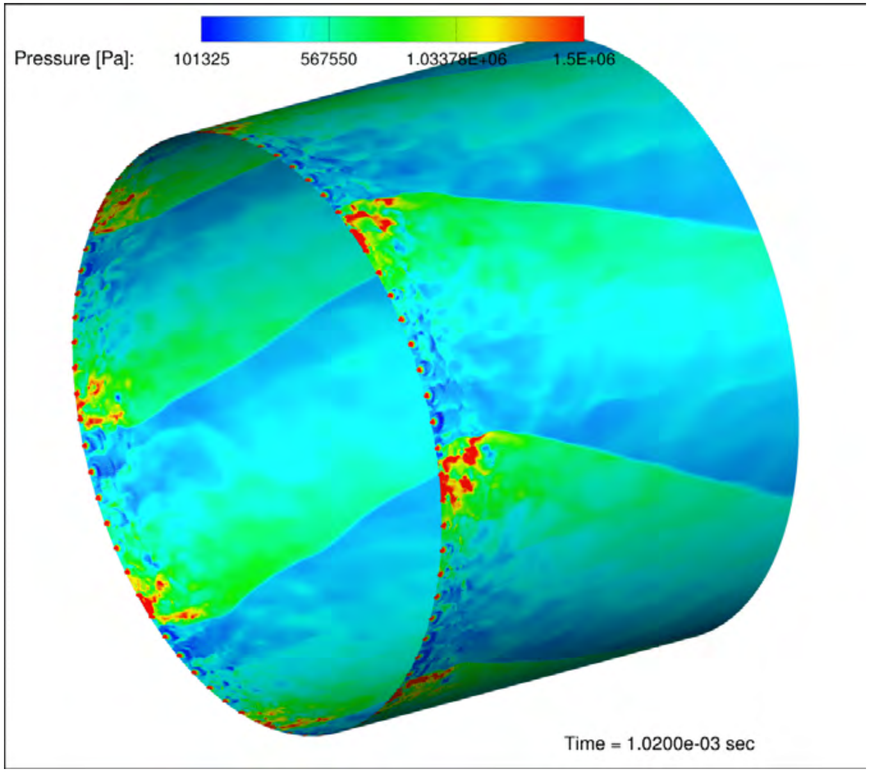


Pressure field during steady operation

- CASE 104 (BASE)



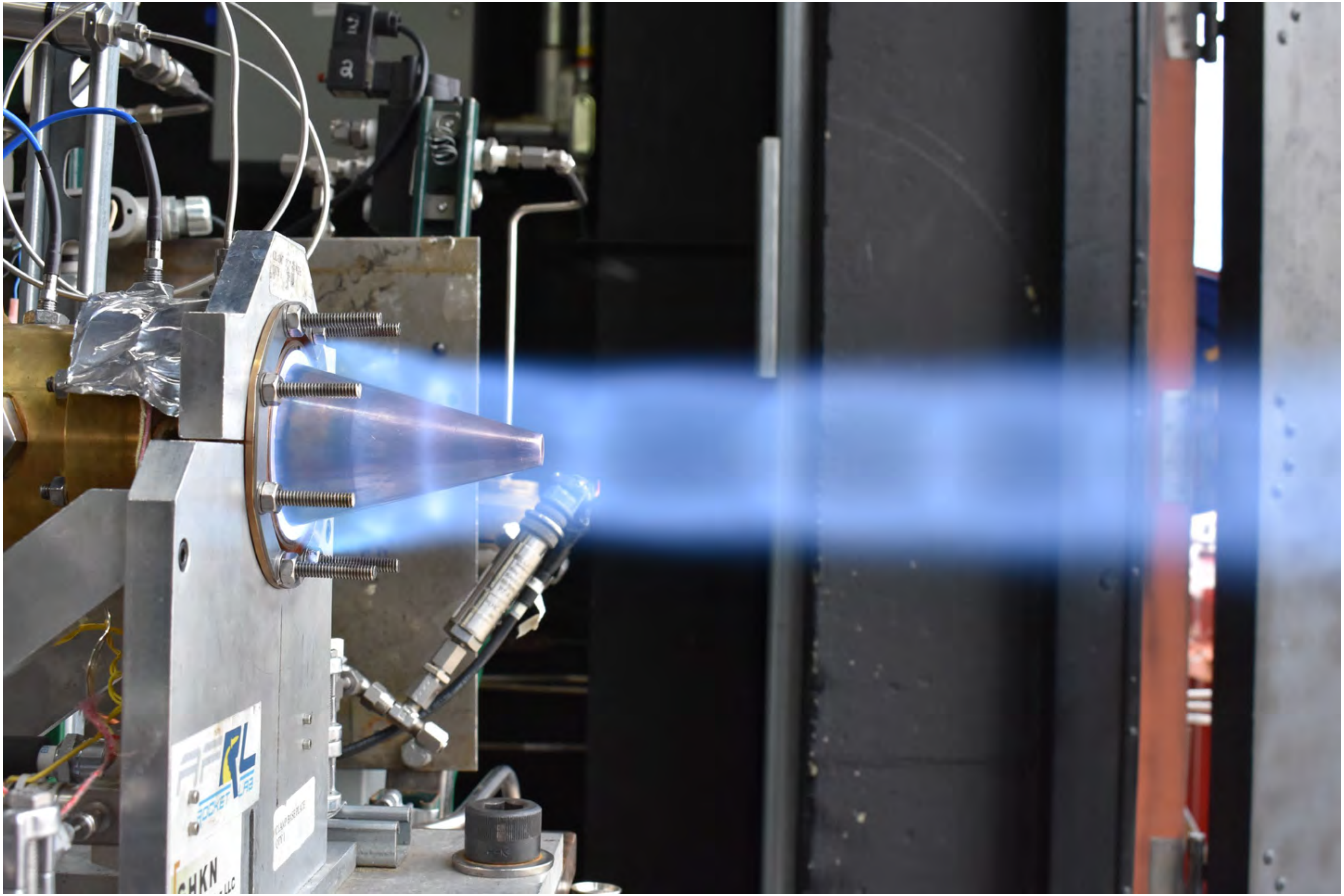
- CASE 124 (HIGH Ṁ)



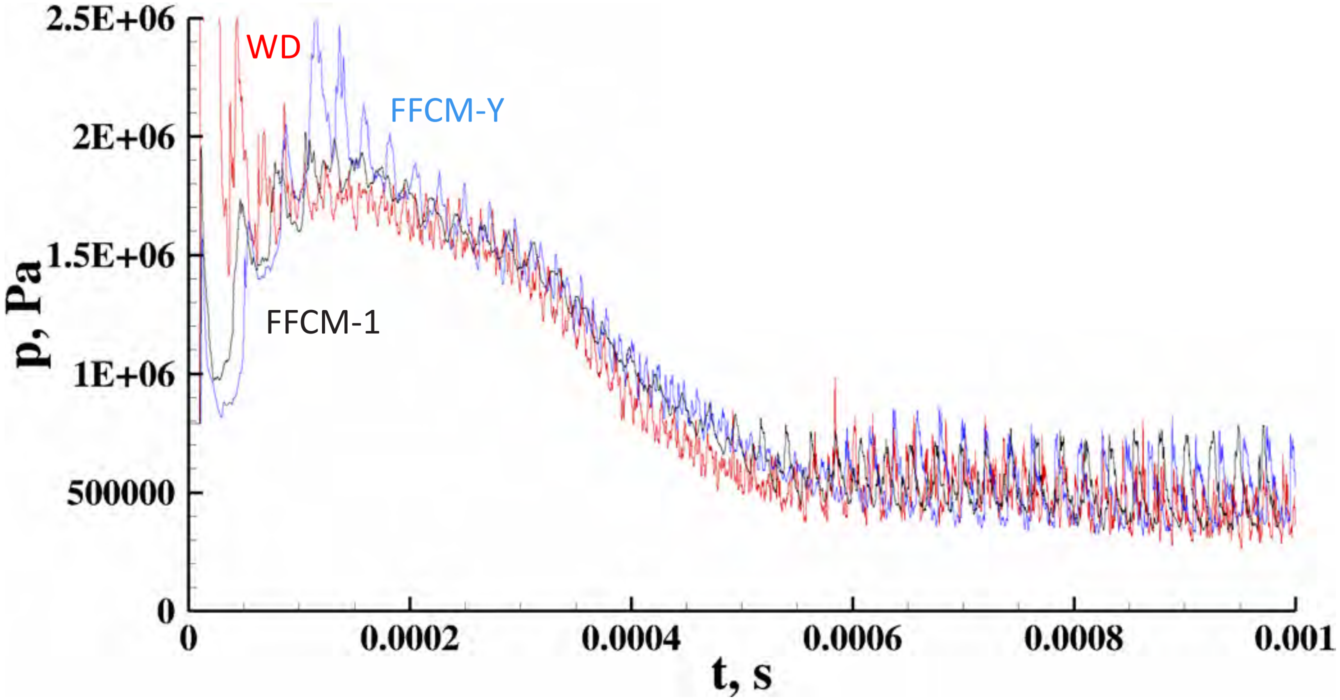
Full Annulus Simulations: Concluding Remarks

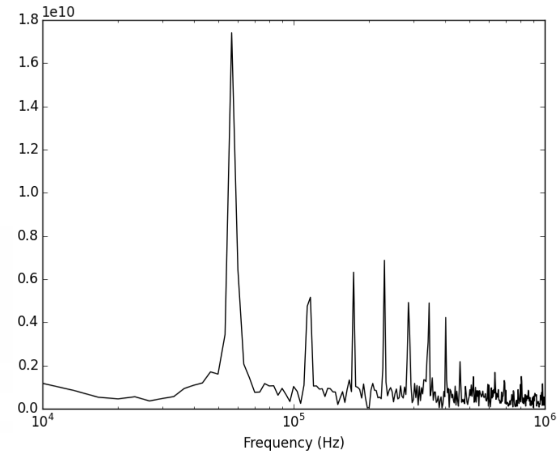
- Number of waves similar to experiments excited naturally
- Start-up behavior is qualitatively similar to experiment, starting from many waves and diminishing toward a quasi-steady state periodicity
- Wave speeds consistently several hundred m/s faster than experiment
  - WD chemistry model yields fast detonation, regardless of premixedness
  - Unmodelled heat loss expected to further decrease speed
- Galloping behavior seen in experiments is primary mechanism for coalescence of waves in simulations as well
- For more information:
  - C. Lietz, Y. Desai, R. Munipalli, S.A. Schumaker, and V. Sankaran. "Flowfield analysis of a 3D simulation of a rotating detonation rocket engine". AIAA Aerospace Sciences Meeting, January 2019.

Questions?



Pressure Trace and Wave Speed



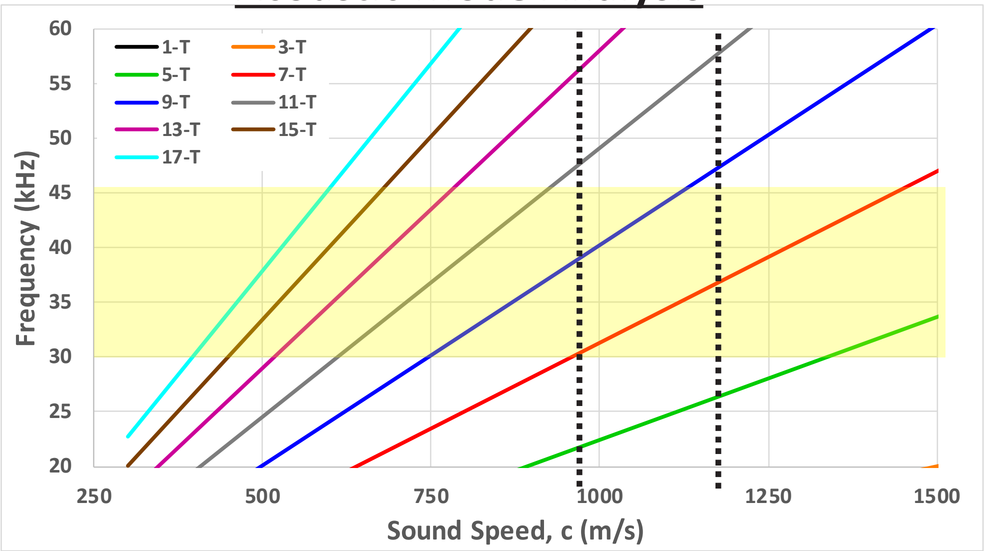


	Experiment	WD	FFCM-Y	FFCM-1
CTAP (psia)	56.5	64.2	70.0	72.2
Wave speed (m/s)	1130	1580	1310	1260
Refresh time (μs)	24.7	17.6	21.3	22.3

Detonation Mode or High-Amplitude Instability?

- Average wave speeds measured ~45% of the CJ velocity in this study.
  - Previous work by GHKN with same model RDRE yielded same performance for equivalent flow conditions but wave speeds closer to 75%.

Acoustic Mode Analysis



- For the RDRE annular geometry, acoustic mode frequencies within the observed operational frequency range (~30-45 kHz) do arise as potential candidates for c = 950 – 1150 m/s.
  - Frequency analysis alone is not sufficient to determine operational regime of RDRE.
- Potentially excited a high-amplitude spinning tangential instability
  - Continuum exists between instability mode and fully-detonative mode.
- Current work is underway to address this point (e.g., measure oscillatory pressure trace).

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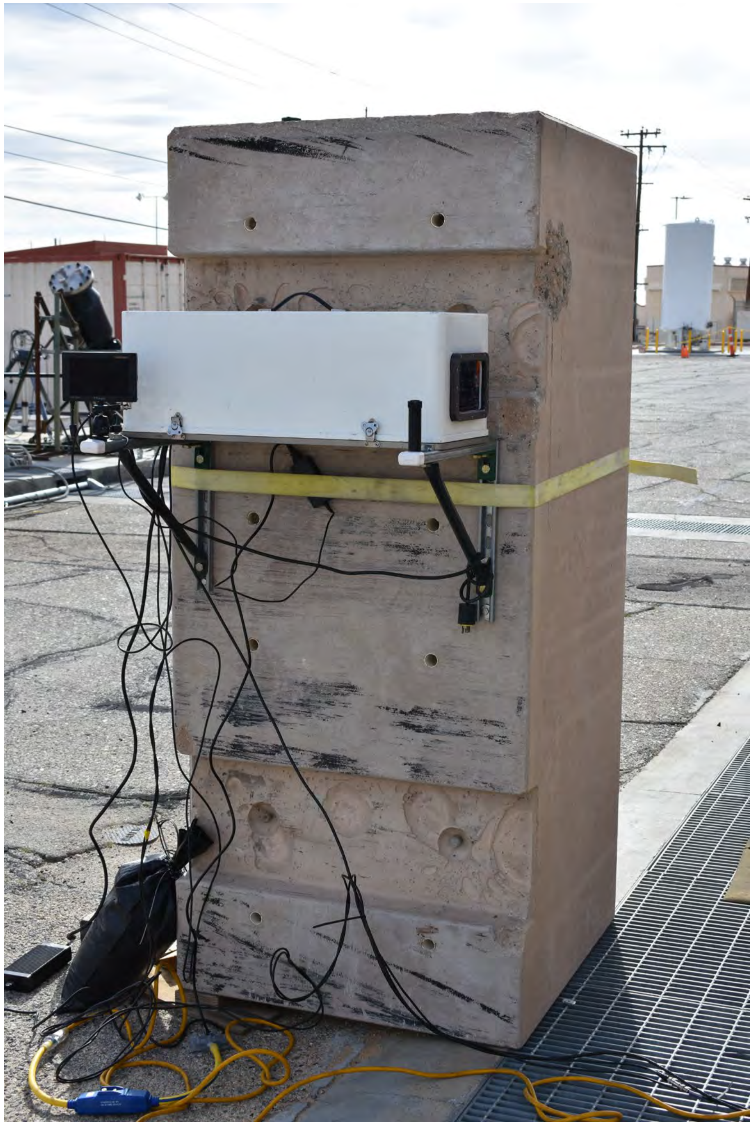
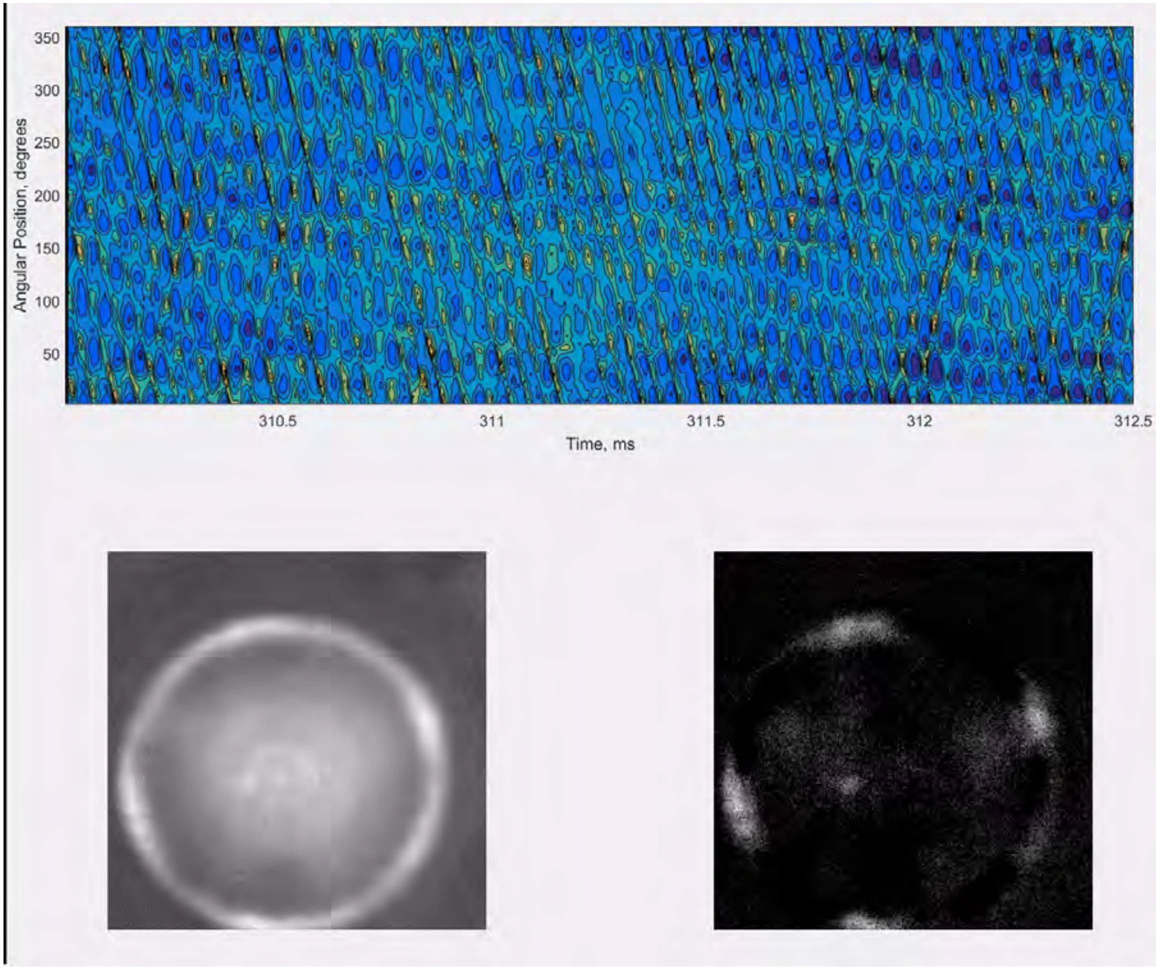
High-Speed Camera Setup



Counter-Propagating Mode Analysis

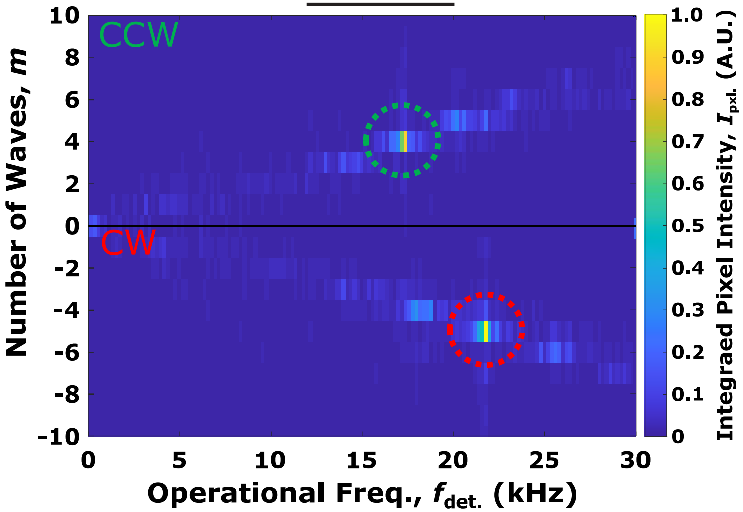
Detonation Surface



Flow Condition: ϕ = 1.1, $\dot{m}_{tot}$ = 0.2 lbm/s

- Opposing wave behavior existed with primarily 5 CW dominant mode with a 4 CCW counter-propagating component.
- Intensity of the counter-propagating component is 83% of the dominant.

2-D FFT



Max. Peak Characteristics

Dom. Num. Waves: m = 5
Operational Frequency: $f_{det.}$ = 22.0 kHz

CP Num. Waves: m = -4
Operational Frequency: $f_{det.}$ = 17.6 kHz