Analysis of Quasi-Steady, Transitional, and Short Timescale Galloping within Rotating Detonation Engines

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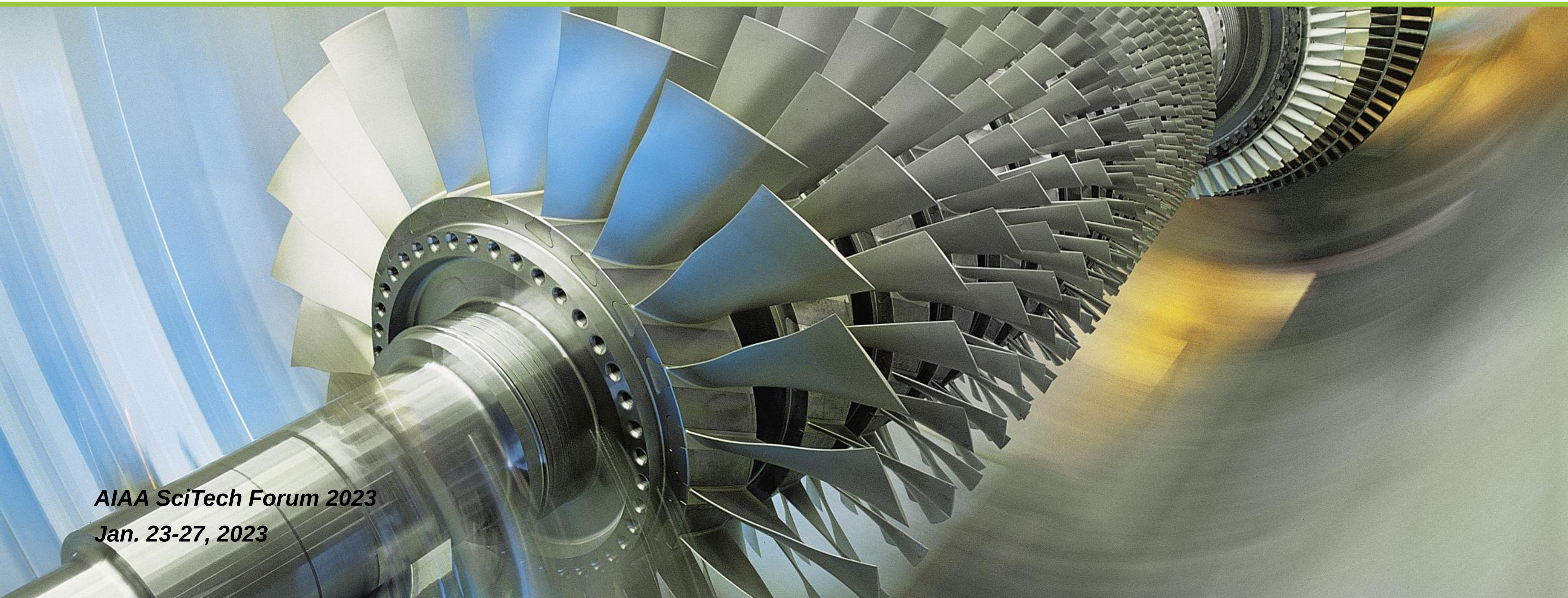

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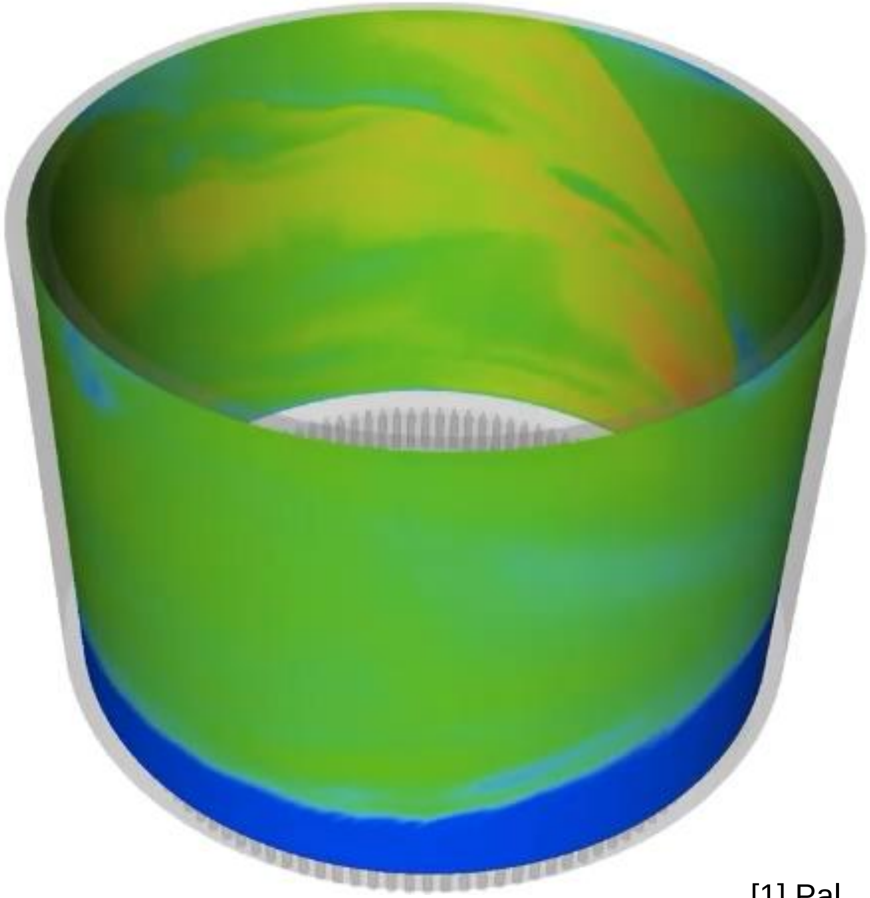
Outline

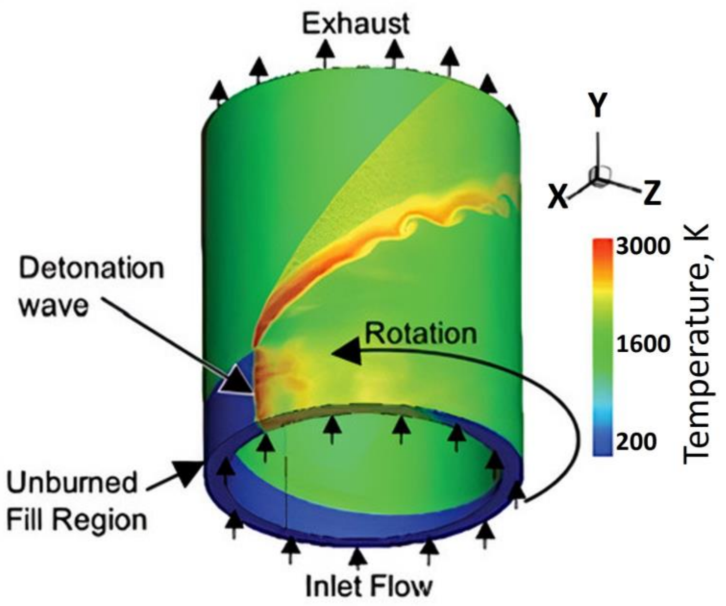
- Introduction
- Experimental Setup
- Method: Galloping surfaces
- Indications of Galloping
- Results
- Discussion: Wave strength
- Conclusion



[1] Pal

Introduction

- Rotating detonation engines (RDEs) offer an alternative strategy for advancing the thermodynamic efficiency of gas turbine engines
- RDE technology has matured to mechanism research
  - RDE modal behavior must be quantified for turbine integration
- A wave mode of interest: long-term, stable ***galloping***
- Galloping waves exhibit periodic oscillations of wave speed and subsequent wave spacing
- Often referred to as an unsteady or transitional behavior leading to mode changes or wave failure
- Galloping is observed in the NETL RDE over extended run times
  - Should be considered as a possible, likely preferred mode of operation



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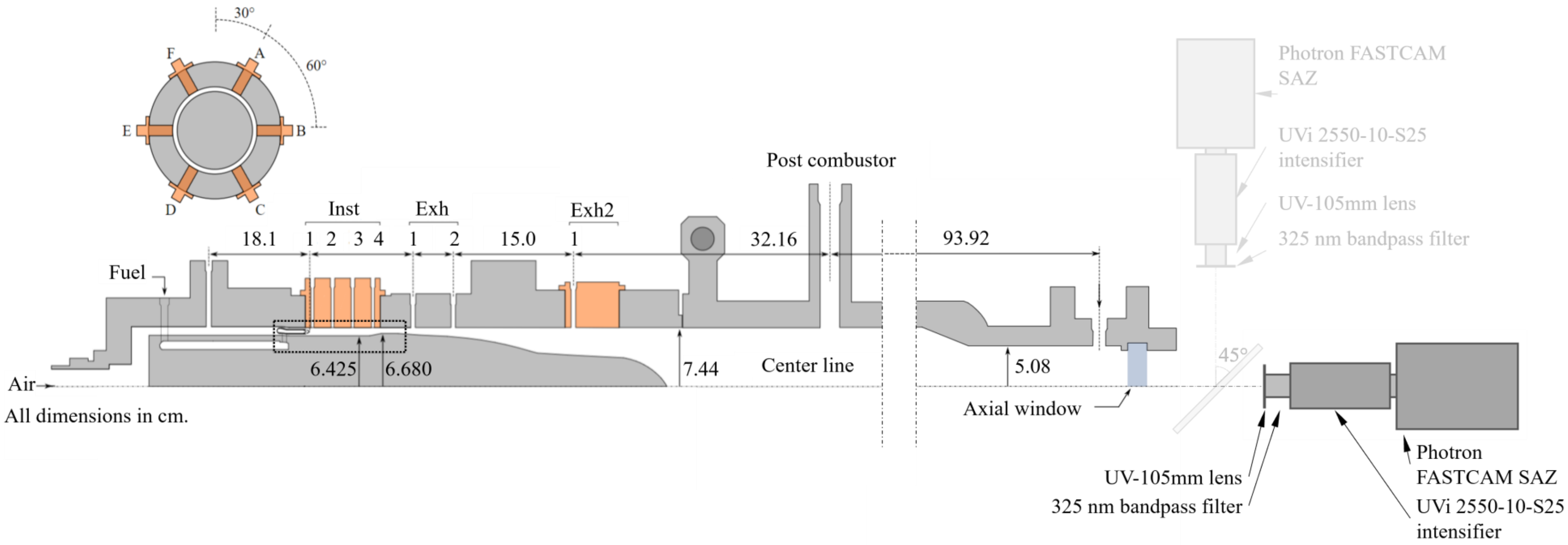
Water-Cooled NETL RDE

- Water-cooled NETL RDE
  - Uncirculated water
  - Run times exceeding 30 seconds
- High-speed axis-aligned imaging



Water-Cooled NETL RDE

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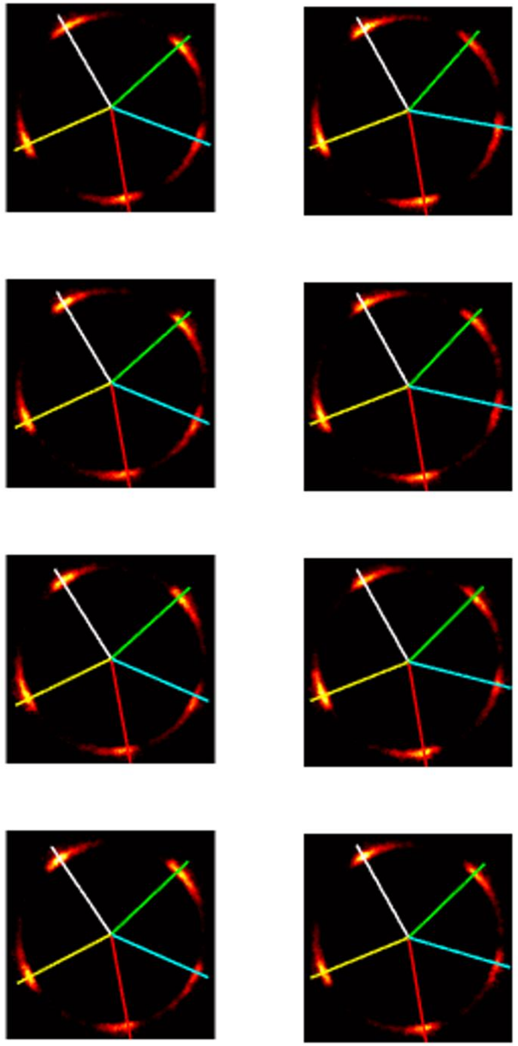
- Water-cooled NETL RDE
  - Uncirculated water
  - Run times exceeding 30 seconds
- High-speed axis-aligned imaging
  - 60,000 fps
  - Photron FASTCAM SA-Z high-speed digital camera
  - OH* Chemiluminescence images
  - UVi intensifier, UV lens, bandpass filter



Method: Galloping Surface

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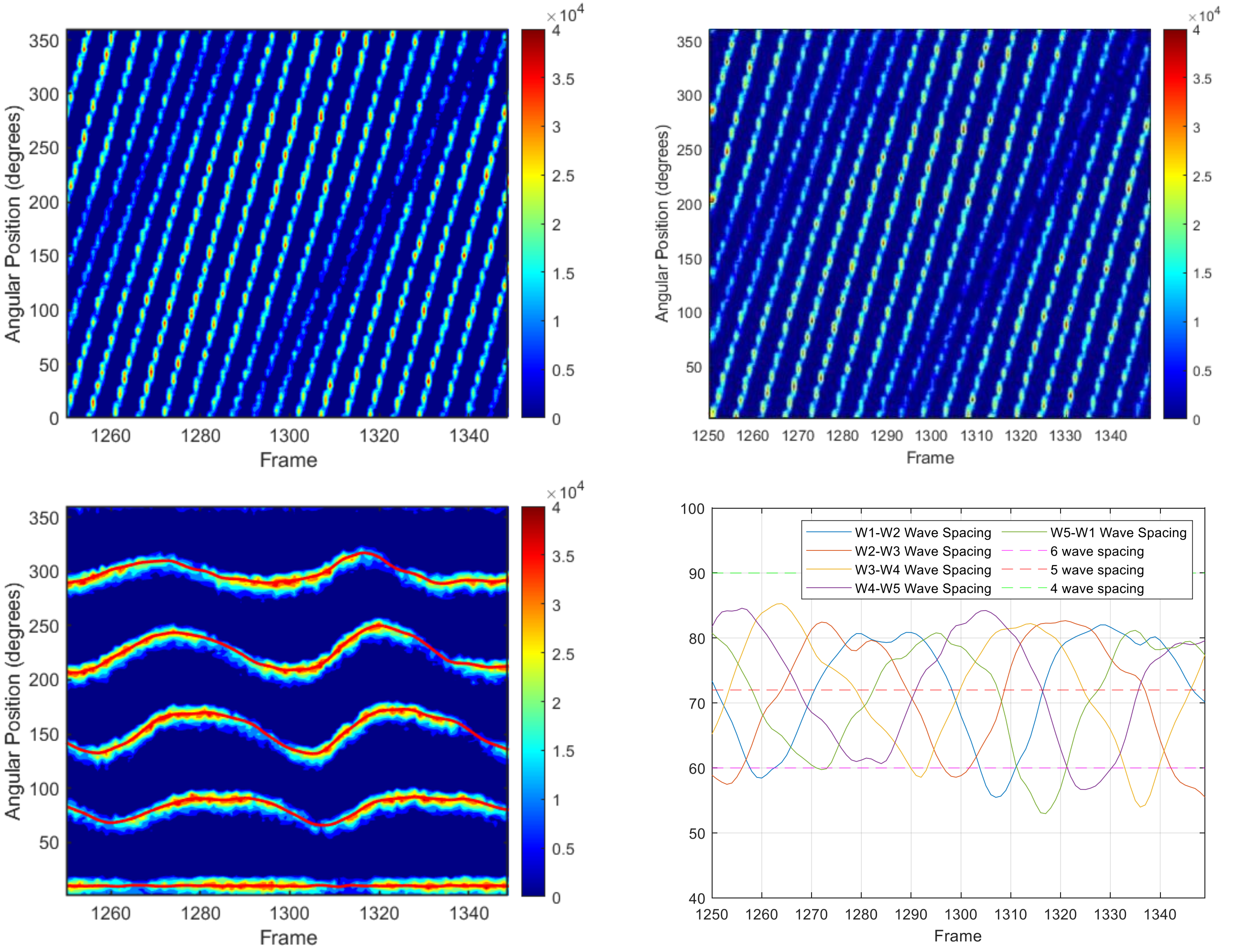
- Beginning with standard detonation surface,
- Cumulative lag:

$$\tau(n) = \sum_{i=1}^{n} [\Theta(:,i) \star \Theta(:,i-1)] \quad \in \quad [2:n]$$

- Values of detonation surface shifted by cumulative lag

$$\Psi(z,n) = \begin{bmatrix} \phi_{1_1} & \phi_{[1-\tau(2)]_2} & \phi_{[1-\tau(3)]_3} & \cdots & \phi_{[1-\tau(N)]_N} \\ \phi_{2_1} & \phi_{[2-\tau(2)]_2} & \phi_{[2-\tau(3)]_3} & \cdots & \phi_{[2-\tau(N)]_N} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \phi_{Z_1} & \phi_{[Z-\tau(2)]_2} & \phi_{[Z-\tau(3)]_3} & \cdots & \phi_{[Z-\tau(N)]_N} \end{bmatrix}$$

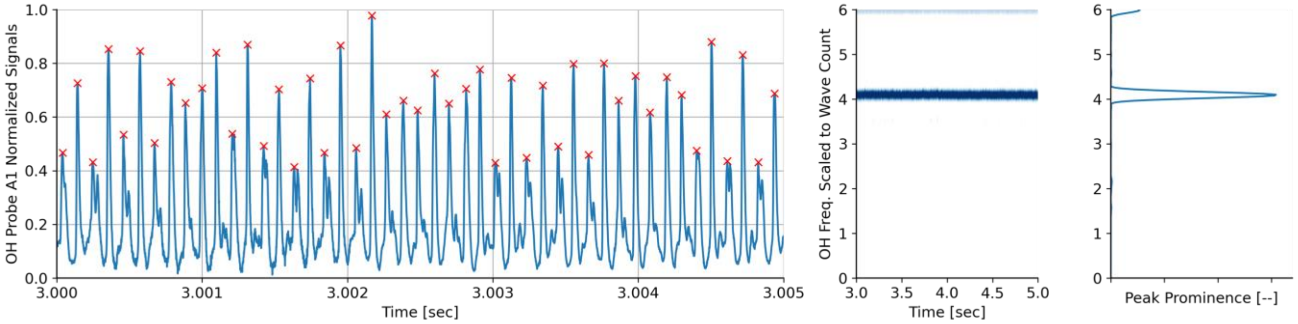
- Final adjustment using primary spline
- Wave spacing extraction



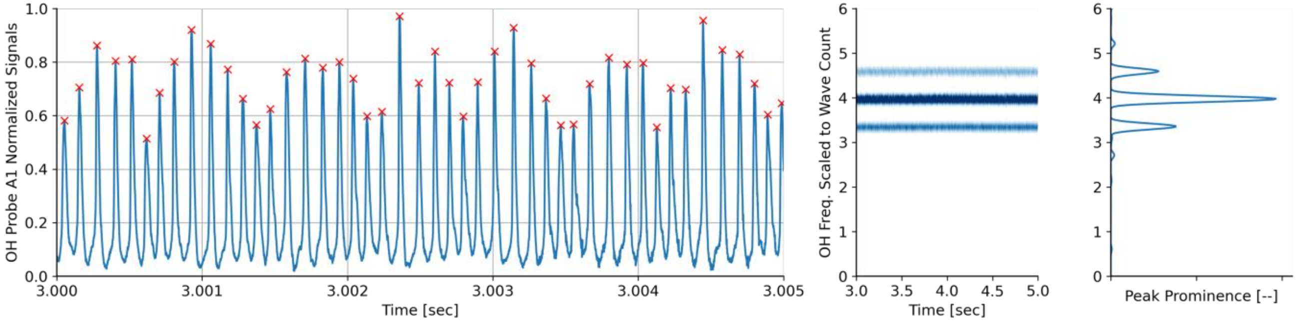
Indications of Galloping

- Galloping wave modes are present in high-speed point measurements
  - Pressures, ion probes, and OH probes
- Hamming windowed spectrogram of the high-speed signal
- Galloping presents side bands on either side of peak carrier frequency
- Two side-band frequencies approach ±1 wave
- Periodic change in signal peak heights can be observed
  - Should be confirmed by high-speed imaging or spectrogram

Non-Galloping Case



Galloping Case



Case Summary

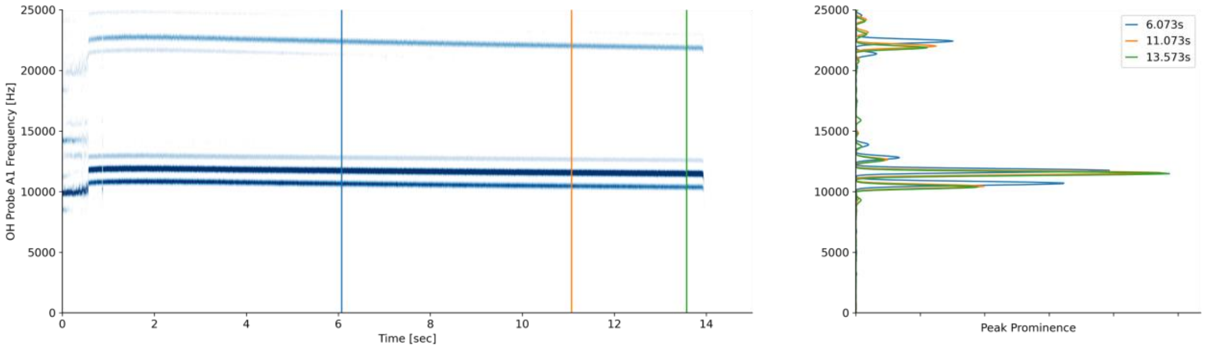
- Galloping wave modes are analyzed as three subgroups:
  - Quasi-steady (Q)
  - Short timescale (S)
  - Transitional (T): resulting from broadly swept equivalence ratios

Type	Wave Count	Case Descriptor	Φ	$\dot{m}$ [KSCFH]	P_{back} [psig]	Imaging setup
Quasi-steady	4	Q4	0.45	65.0	0	Perpendicular
	5	Q5	$0.68 \rightarrow 0.52$	101.0	0	Center-aligned
Short Timescale	2	S2	0.9	75.3	0	Perpendicular
	4	S4	0.6	65.0	0	Perpendicular
Transitional	4-5	T45	$0.95 \rightarrow 0.44$	101.0	10	Center-aligned
	5-4	T54	$0.43 \rightarrow 0.84$	101.0	10	Center-aligned

Table 1 Summary of galloping cases presented in the following subsections

Galloping – Case Q5

- 5 quasi-steady galloping waves
- Sideband present in Fast Fourier Transforms (FFTs)



Galloping – Case Q5

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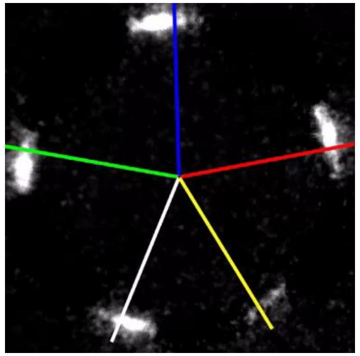
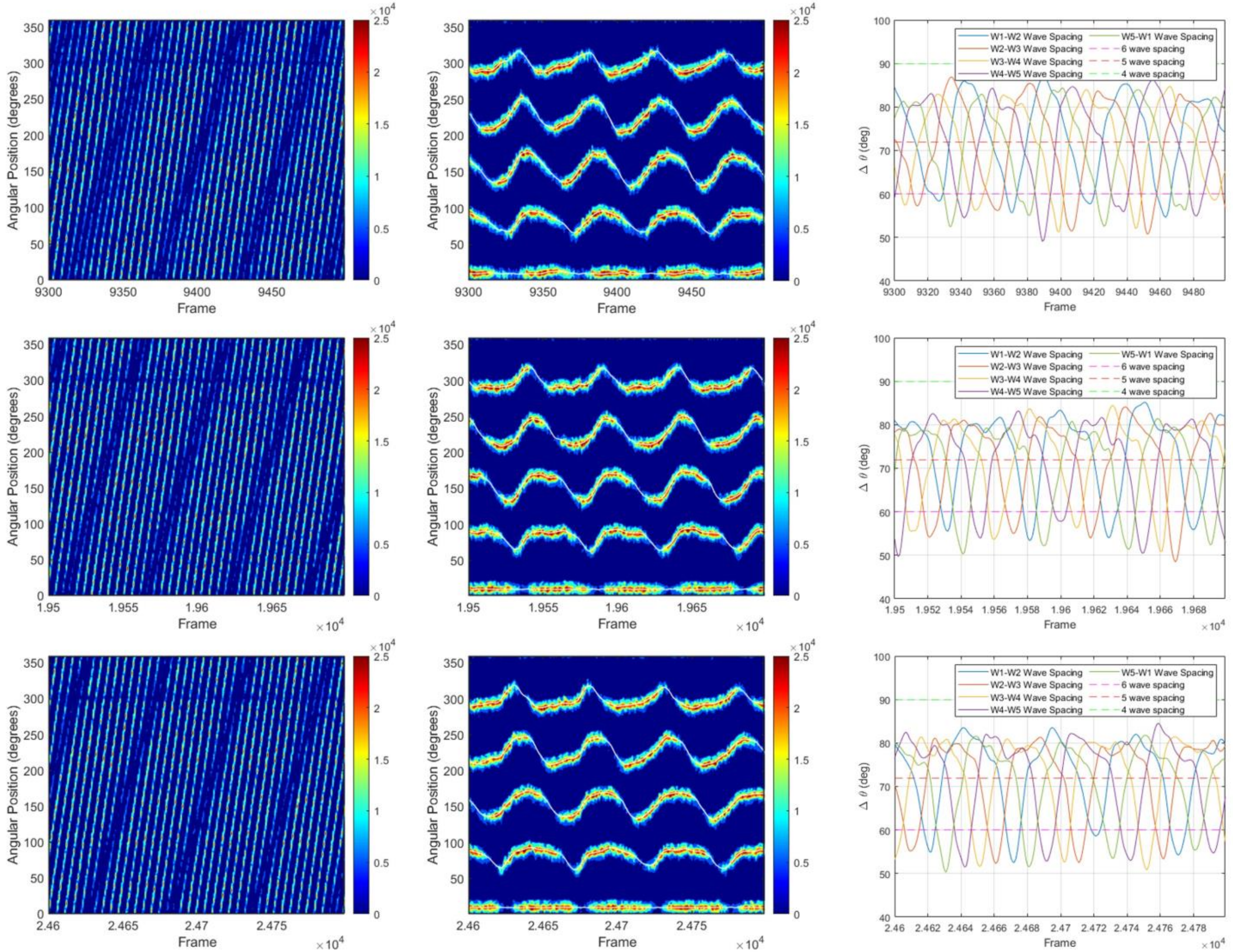
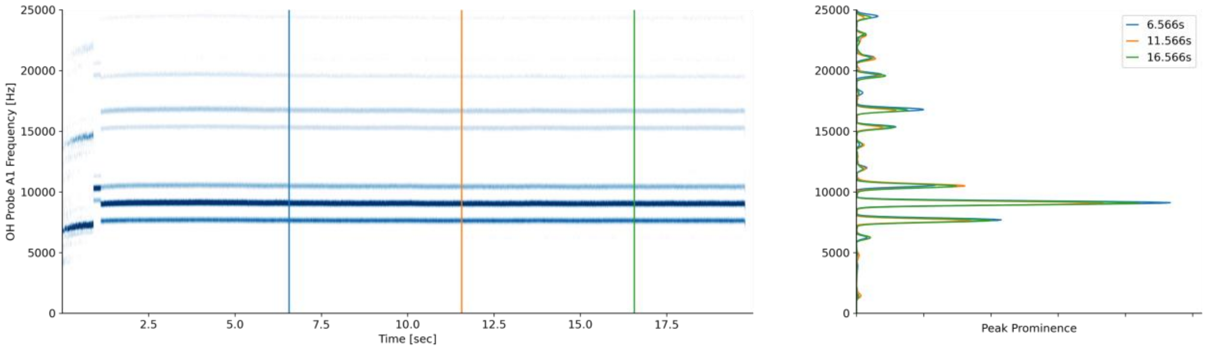
- 5 quasi-steady galloping waves
- Sideband present in Fast Fourier Transforms (FFTs)
- Stable through 14 second run
- Decreasing equivalence ratio (0.68 → 0.52) causes decreasing carrier frequency





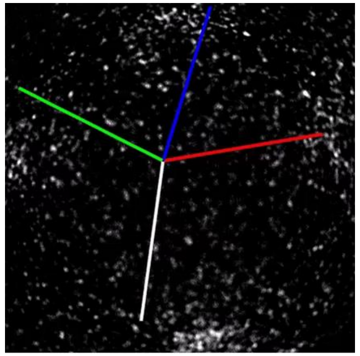
Galloping – Case Q4

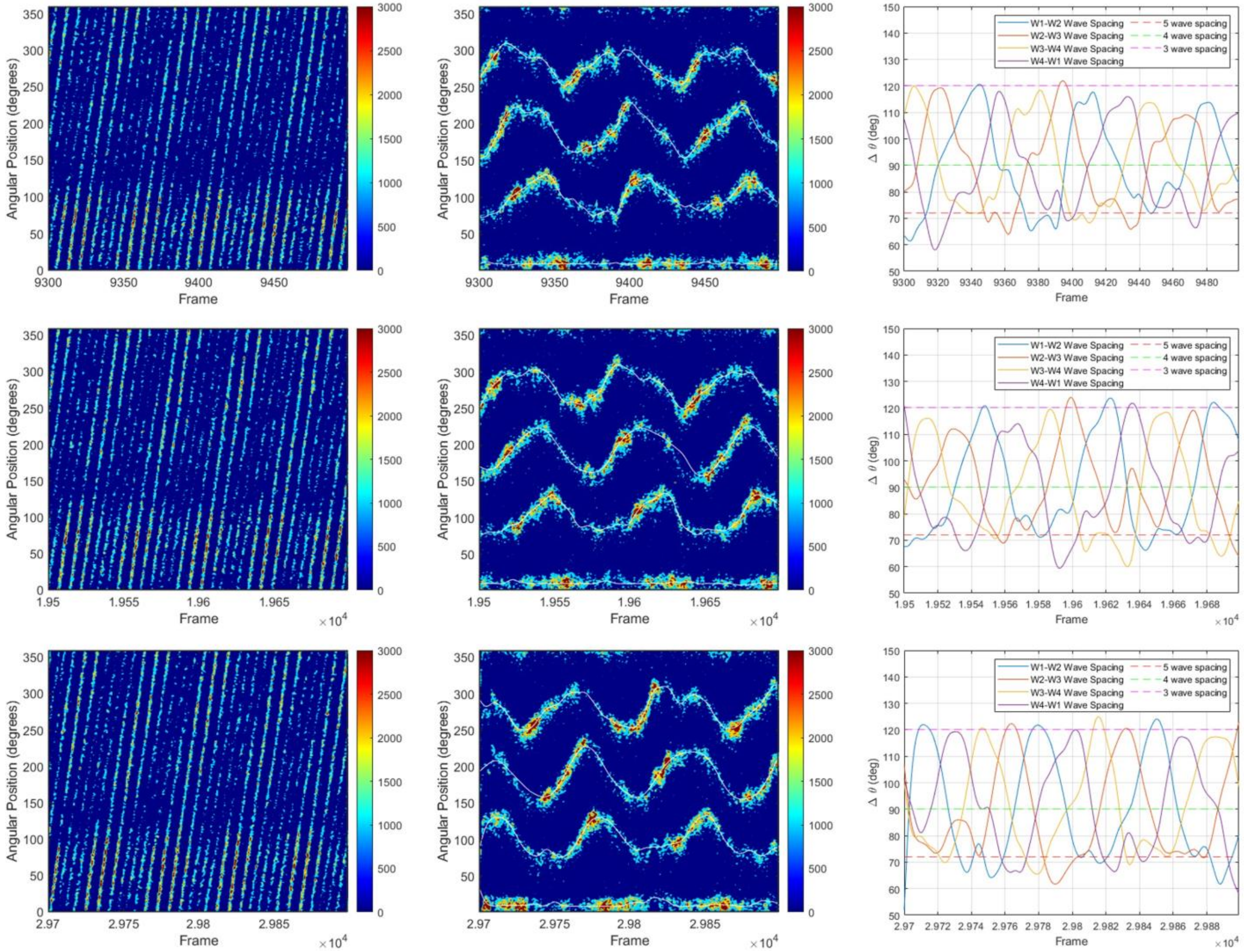
- 4 quasi-steady galloping waves
- Sideband present in FFTs



Galloping – Case Q4

- 4 quasi-steady galloping waves
- Sideband present in FFTs
- Stable through >18 second run
- Wave spacing oscillating between that of ±1 wave



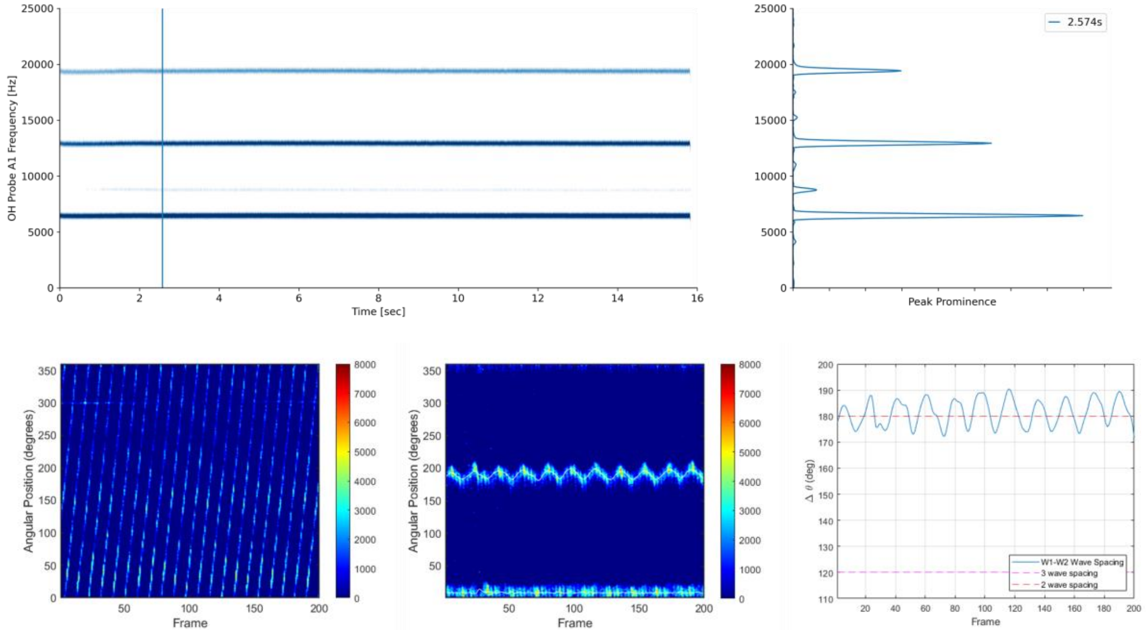


Galloping – Cases S2 and S4

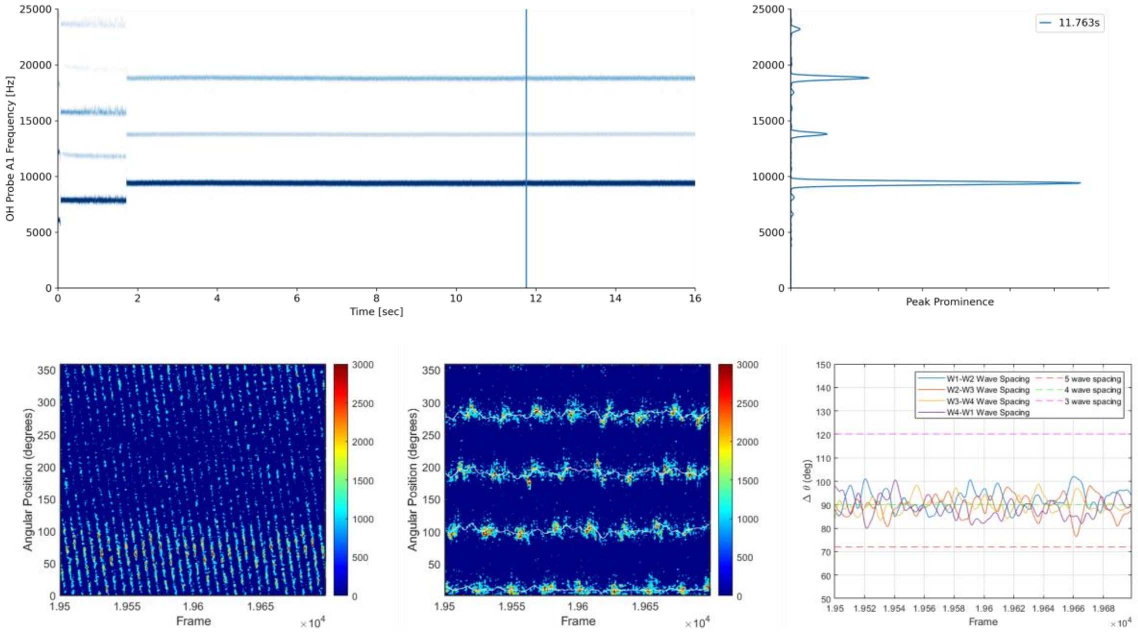
- Wave spacing variation occurs also within short time and length scales
- Indications of galloping are not present in spectrogram
- Wave spacing is never strictly uniform

- No event needed to initiate non-uniform wave spacing
- Certain process parameters lead to dynamic states which promote existing non-uniformities into steady galloping modes

Case S2

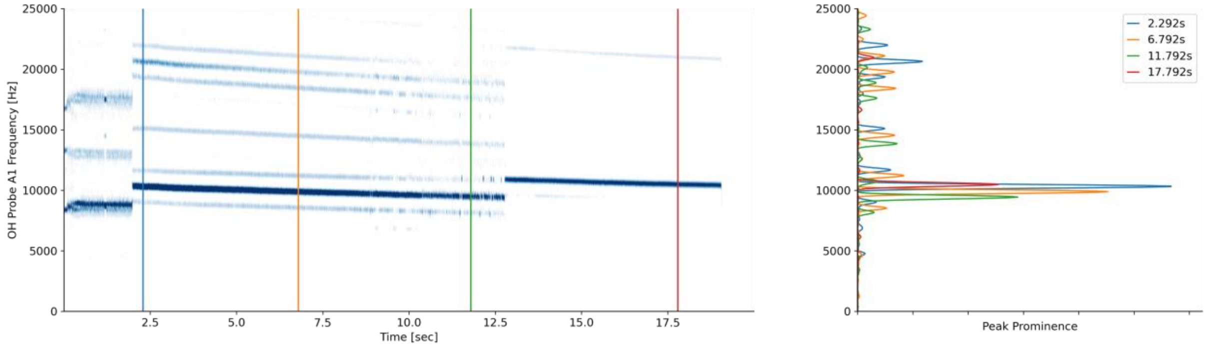


Case S4



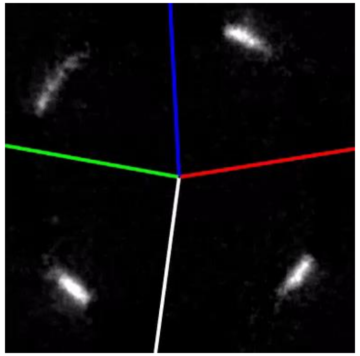
Galloping – Case T45

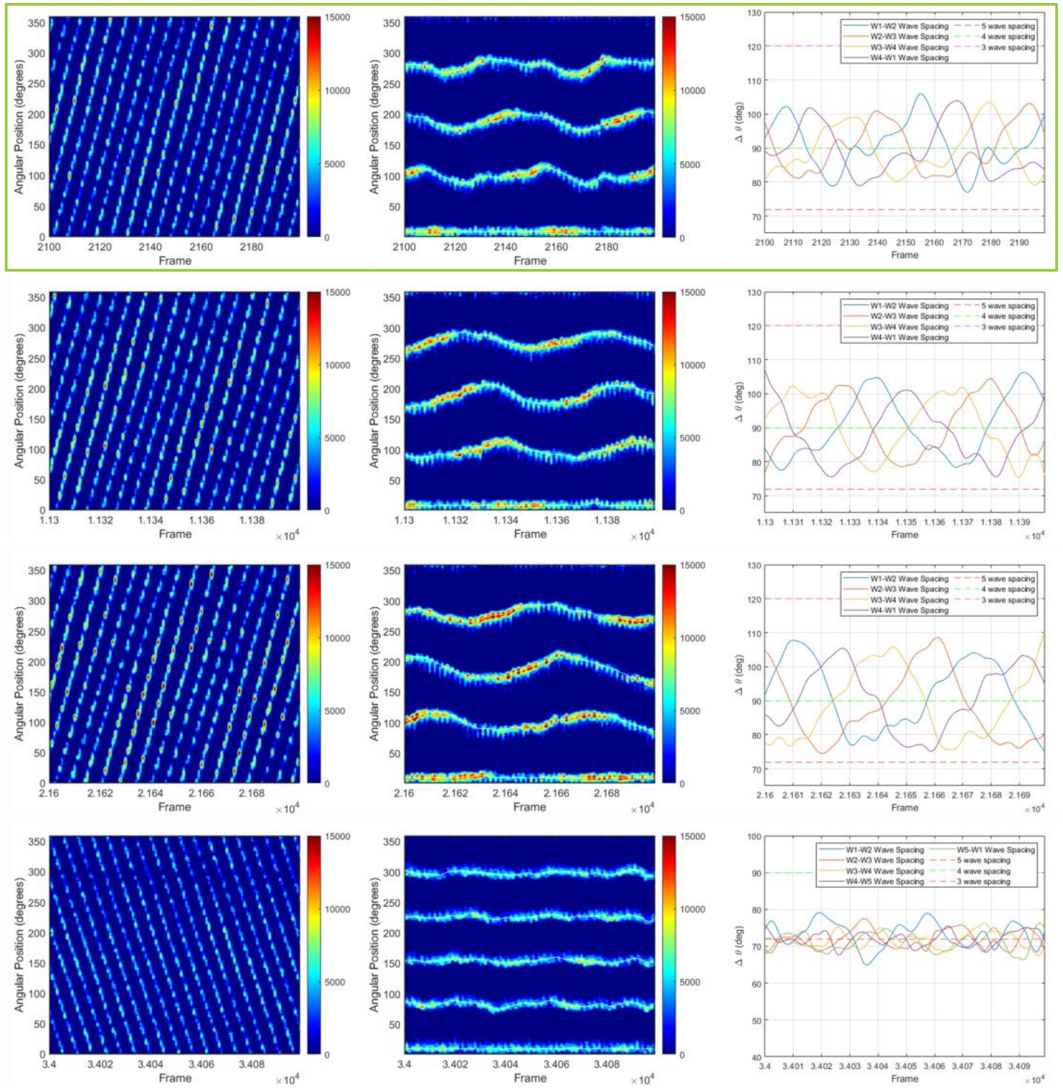
- Transitional galloping waves: 4 → 5
- Decreasing equivalence ratio: 0.95 → 0.44



Galloping – Case T45

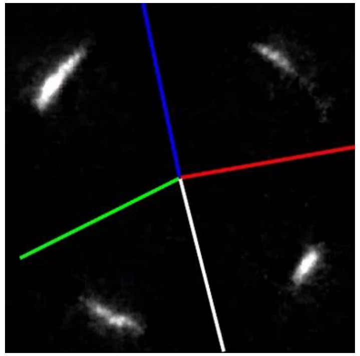
- Transitional galloping waves: 4 → 5
- Decreasing equivalence ratio: 0.95 → 0.44
- Periodic wave spacing deviation increases with lowering equivalence ratio: ±10° → ±15° → ±20°

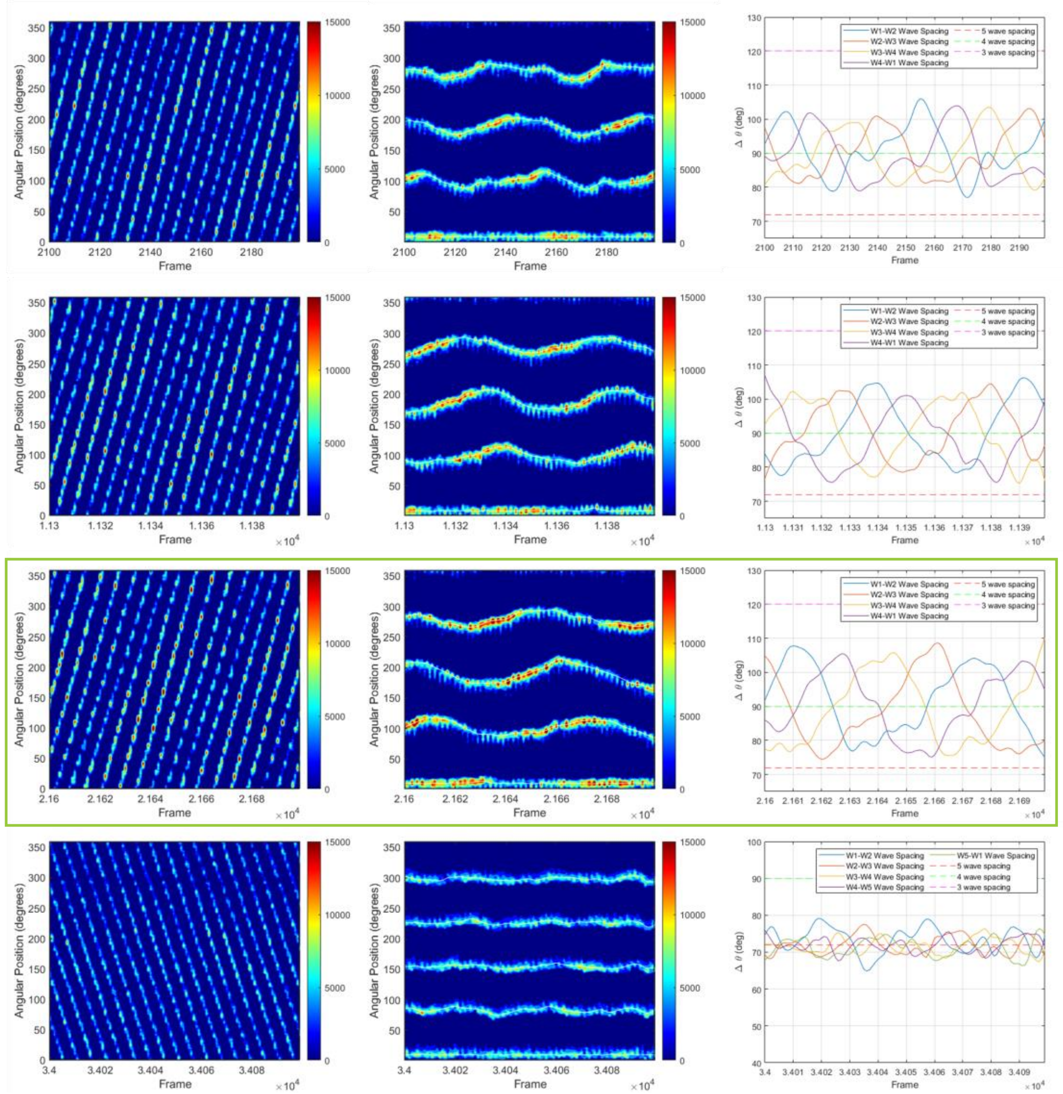




Galloping – Case T45

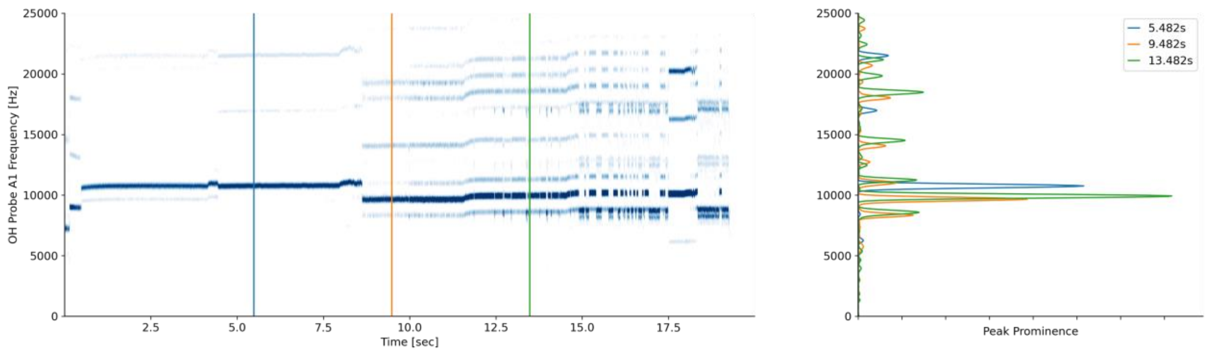
- Transitional galloping waves: 4 → 5
- Decreasing equivalence ratio: 0.95 → 0.44
- Periodic wave spacing deviation increases with lowering equivalence ratio: ±10° → ±15° → ±20°
- Period of galloping is broadened
  - Leads sparsity of spectrogram side bands





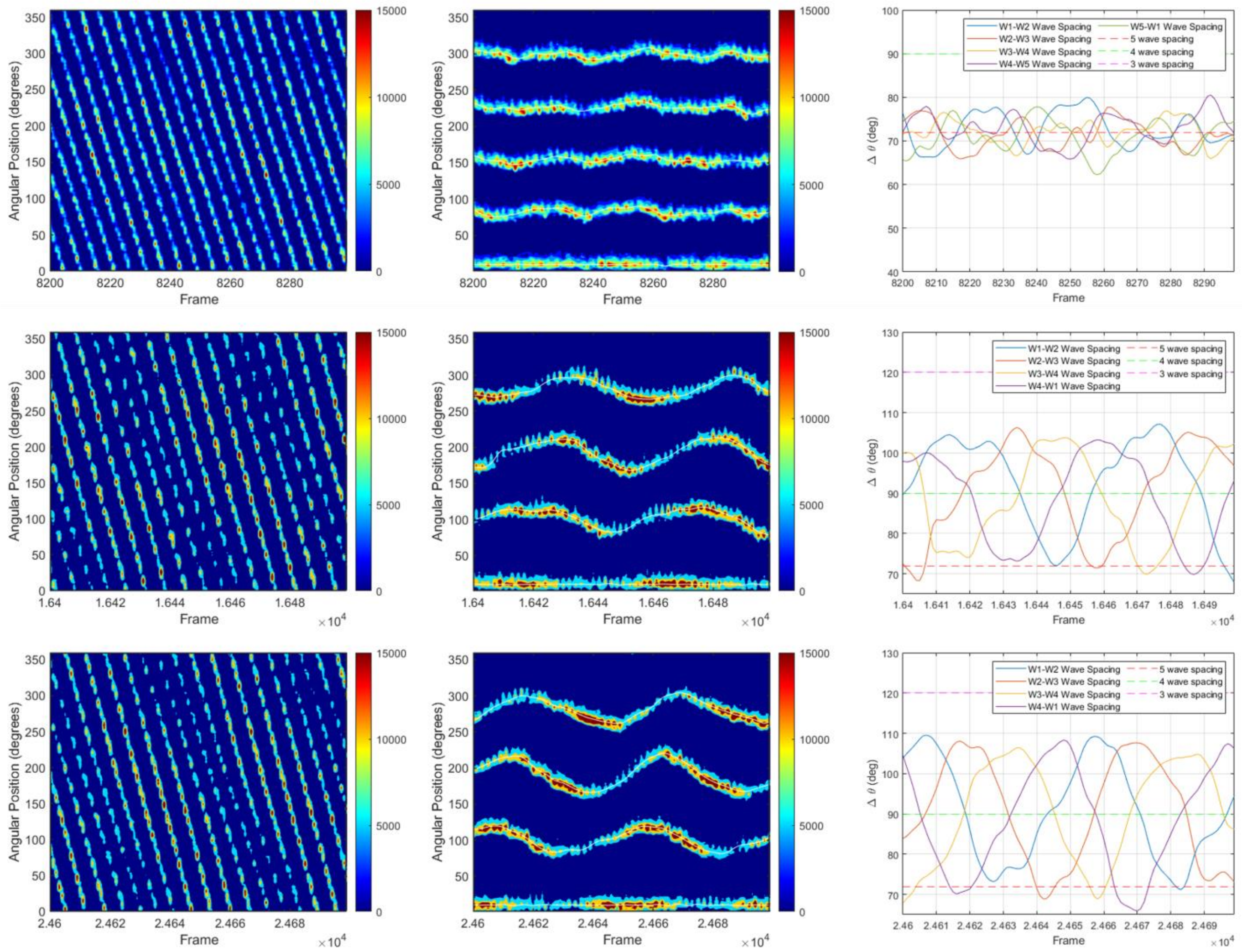
Galloping – Case T54

- Transitional galloping waves: 5 → 4
- Increasing equivalence ratio: 0.43 → 0.84
  - Step changes



Galloping – Case T54

- Transitional galloping waves: 5 → 4
- Increasing equivalence ratio: 0.43 → 0.84
  - Step changes
- Period of galloping is shortened
  - Leads to strengthened spectrogram side bands
- Reversed trend of equivalence ratio to wave mode

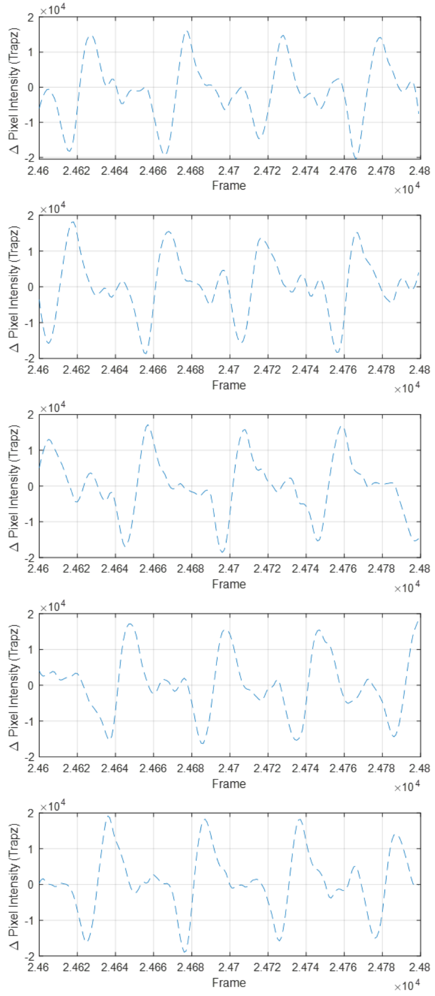


Discussion – Wave Strength

- Using pixel intensity of OH chemiluminescence images as relative measure of wave strength
- Using splines, S_W, fit to each wave, wave intensity is extracted:

$$\xi_W(n) = \Psi(S_W(n), n)$$

- Wave-to-wave pixel difference
- Trends:
  - Positive values: stronger leading wave
  - Negative values: stronger lagging wave
  - Positive slopes from negative to positive values: weaker leading wave becoming stronger to a point of equality at the $\xi_{A-B}(n) = 0$ threshold

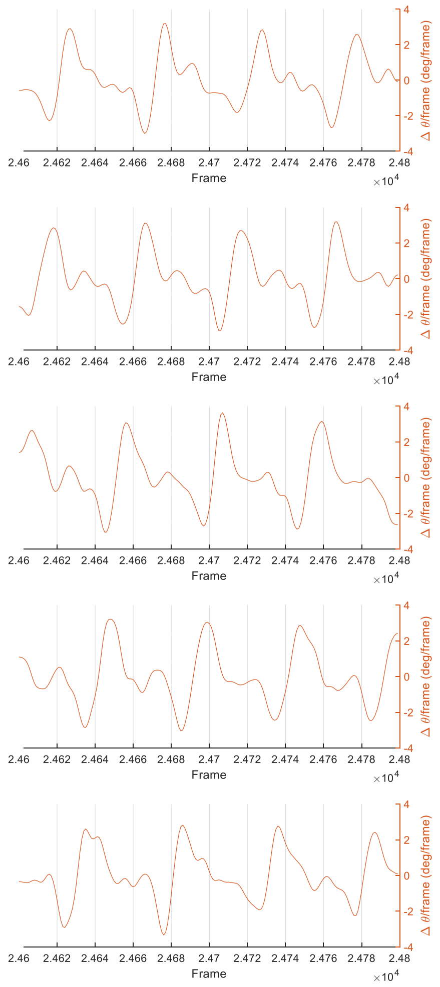


Discussion – Wave Strength

- Using splines, S_W, fit to each wave, differentiated wave spacing:

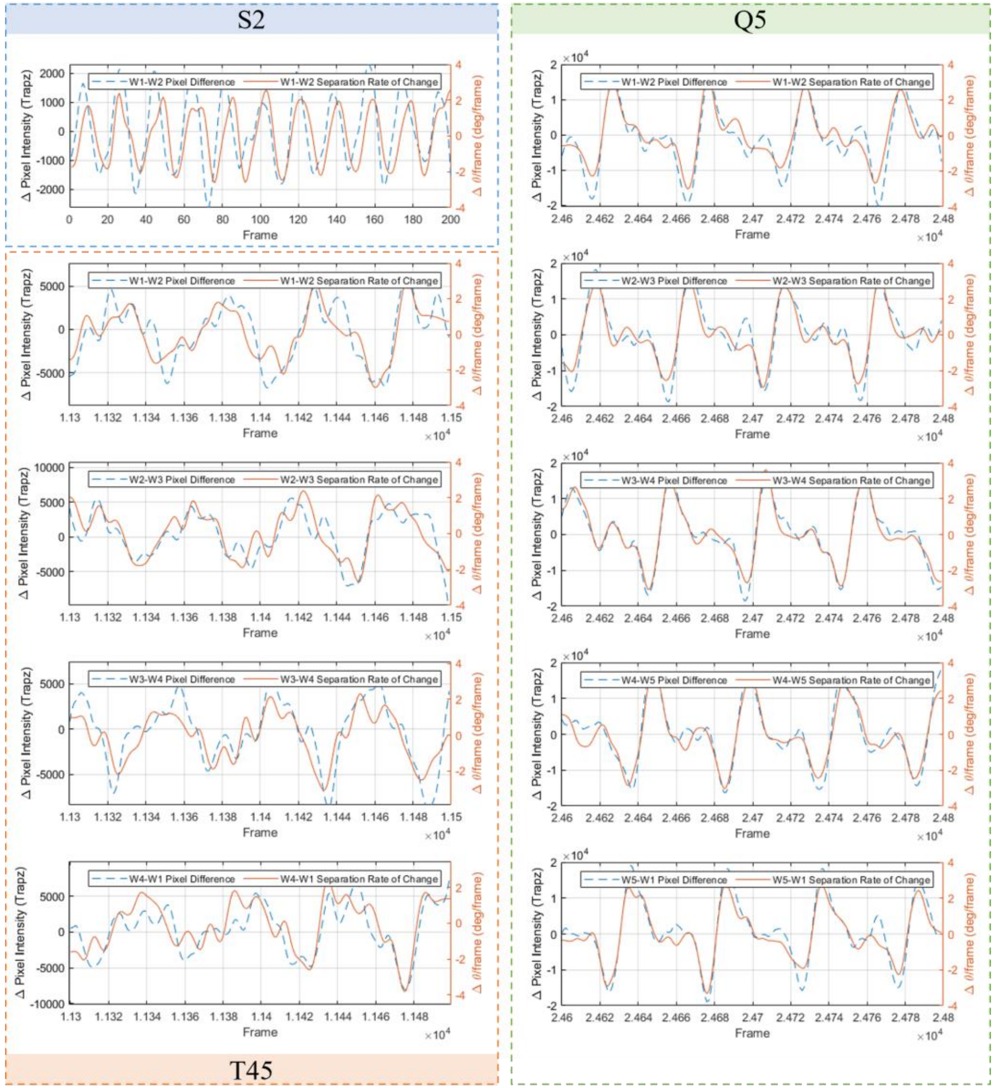
$$\Delta\beta_{A-B}(n) = \frac{d\left(S_B(n) - S_A(n)\right)}{dn}$$

- Wave-to-wave galloping acceleration
- Trends:
  - Positive values: angular separation between two waves increases
  - Negative values: decreasing wave separation
  - Positive slopes $\Delta\beta_{A-B}(n) = 0$ threshold: minimum wave spacing
  - Negative slopes $\Delta\beta_{A-B}(n) = 0$ threshold: maximum wave spacing



Discussion – Wave Strength

- Wave strength and galloping acceleration for individual wave sets are directly associated
- Shared trends:
  - Positive values: stronger leading wave and an increasing wave separation
  - Negative values: stronger lagging wave and decreasing wave separation
  - Shared zero values: equal wave strength, and maximum or minimum wave separation



Conclusions

- Galloping wave modes are observed over extended run times
- Indications of galloping are present in time series data (side bands) and high-speed imaging
- Method for *galloping surfaces* was presented
- Galloping exists as a unique dynamic state of the system/process conditions
  - Process flow rates, back pressure, and pre-heat temperatures
- Galloping modes exist in unique portions of the operating envelope, showing repeatable behaviors
- Stable across equivalence ratio sweeps
  - Possible application to ramp rates in gas turbines
- Galloping waves exchange available fill height for wave strength
- Oscillations in wave strength result in local galloping acceleration
  - Does not lead to mode change, should not be regarded as short timescale instability

References

[1] Pal, Pinaki. *Simulating Supersonic Combustion in a Rotating Detonation Engine*. *YouTube*, Convergecfd, 4 Jan. 2019, www.youtube.com/watch?v=-5KtQ8YvdXI&t=4s.

[2] C. Nordeen, D. Schwer, F. Schauer, J. Hoke, B. Cetegen, and T. Barber, “Thermodynamic Modeling of a Rotating Detonation Engine,” Jan. 2011, doi: doi:10.2514/6.2011-803.

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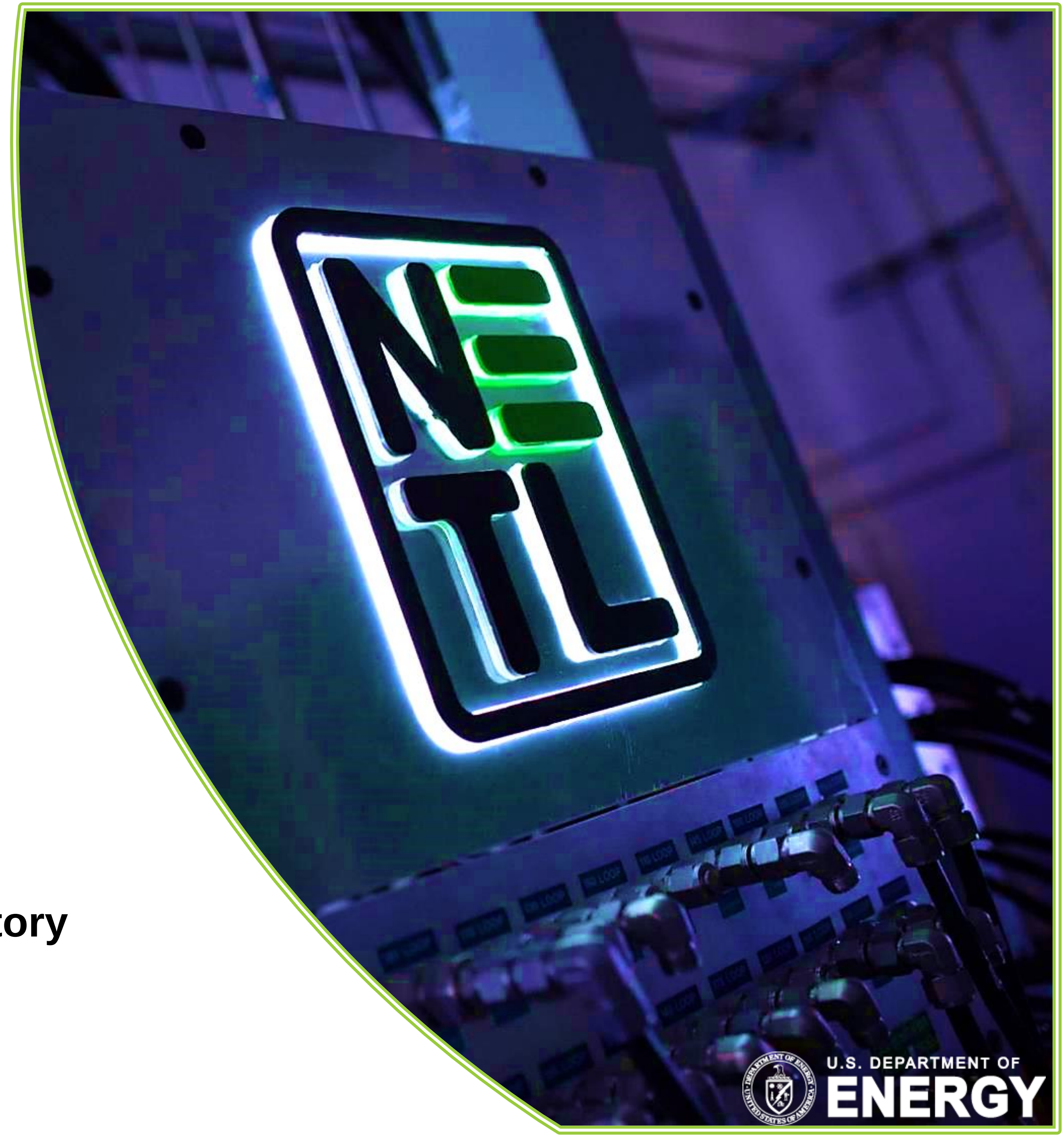

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