# Extremely Low NOx Axial Stage Combustion System

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siemens.tld

# *Presentation Outline*

1. SIEMENS Approach
2. Technology Background
3. NOx Reduction Enablers
4. Demonstrated Results
5. Future Work
6. Conclusions
7. Questions

# SGT-8000H series: ~ 1,000,000 Fired Hours Fleet Experience on Four Continents

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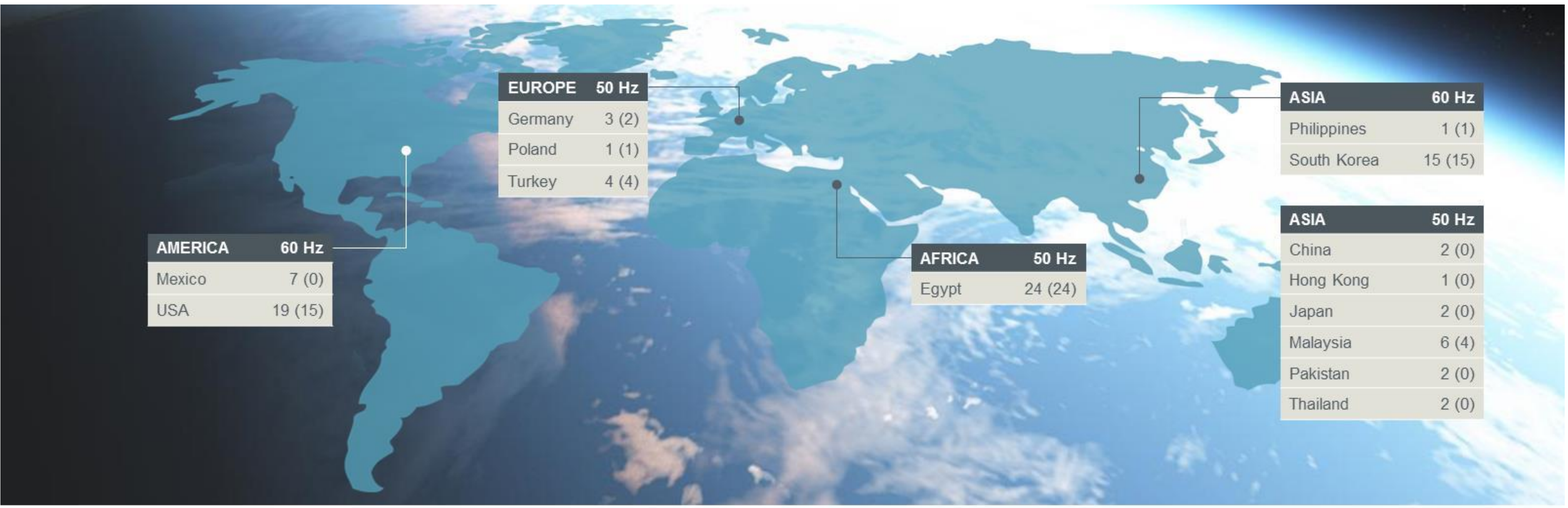


**89** Siemens H-class are under contract

**66** units are in commercial operation

Numbers of sold units (thereof in commercial operation)
Status: September 2018

# Evolutionary Design Based on the Architecture of Siemens H- and F-Class: Decades of Proven Technology Come Together

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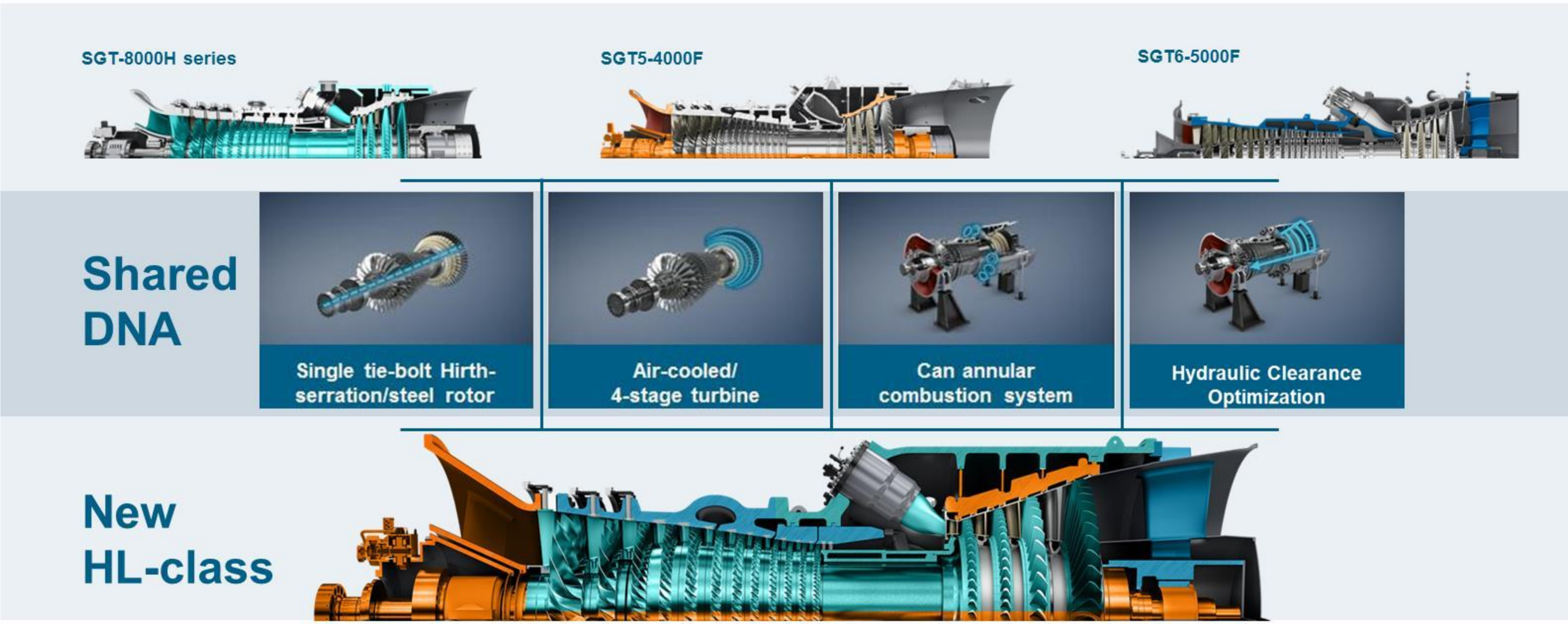

# Siemens HL-class – Competitive Engines for Challenging Markets

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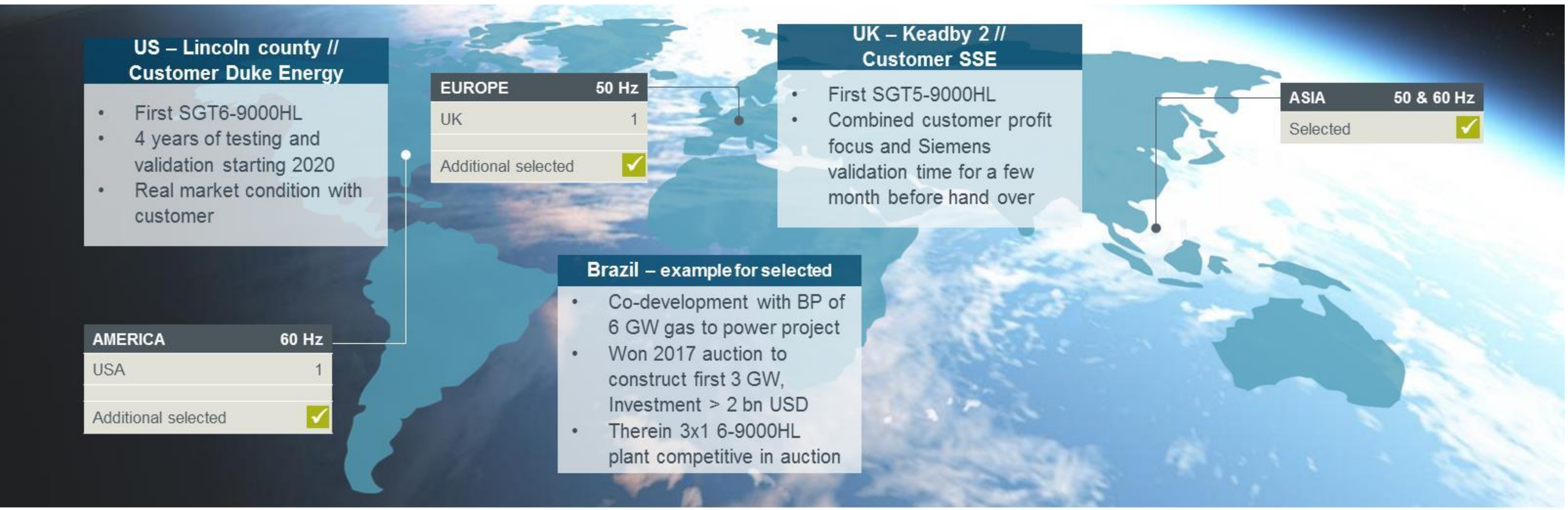


**2** Siemens HL-class are under contract

**Several** units are technical selected

# *Background – Technology Introduction and Current Development Status*

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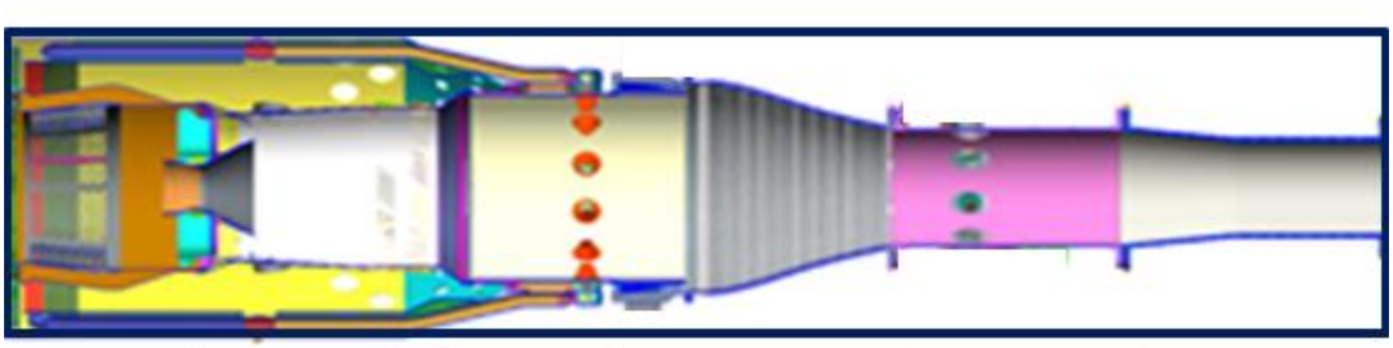
## Proof of Concept Hardware



Head End

Standard
Residence Time
Axial Stage

Ultra Low
Residence Time
Axial Stage

Accelerated cross flow enables:

- Shortened flame
- Further reduced residence time
- Increased pre-flame mixing

- **Proof of concept hardware demonstrated potential for high efficiency GT with low NOx emissions through ultra low residence time secondary stage**
- **Enabler for 65% efficiency**

**Substantial improvement in NOx emissions demonstrated**

# Background – Levers for Increased Firing Temperature with Low NOx

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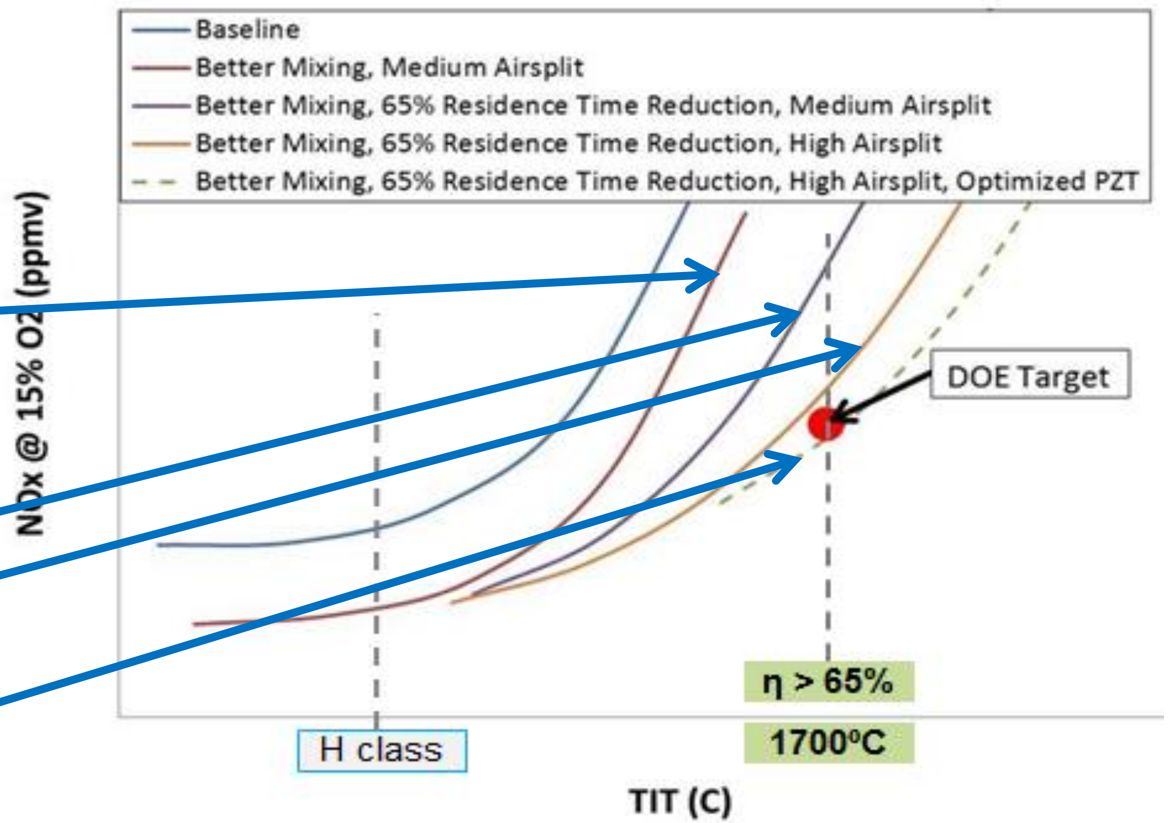
**NOx Reduction Enablers:**

1. High rate of entrainment of dilution gases into axial stage flame
2. Minimal axial stage residence time
3. High air-split
4. High performance primary zone combustor




**Combined approach puts 65% CC efficiency target within reach**

# *NOx Reduction Phenomena Utilized*

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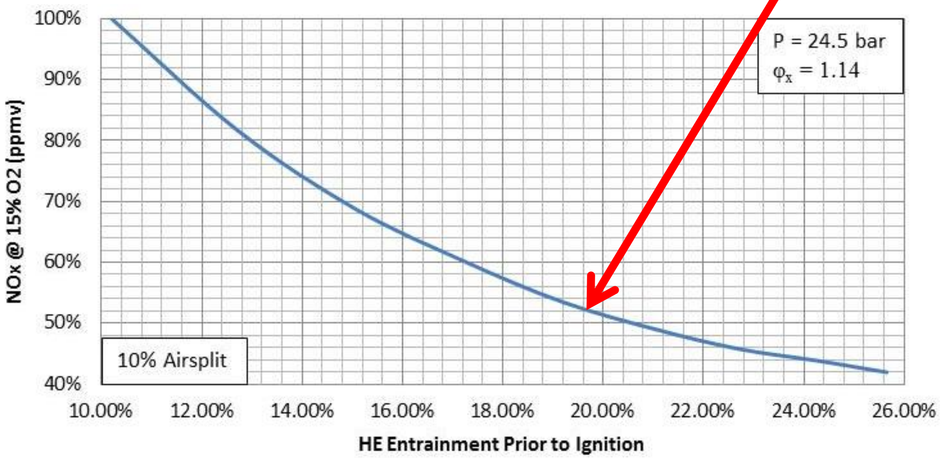
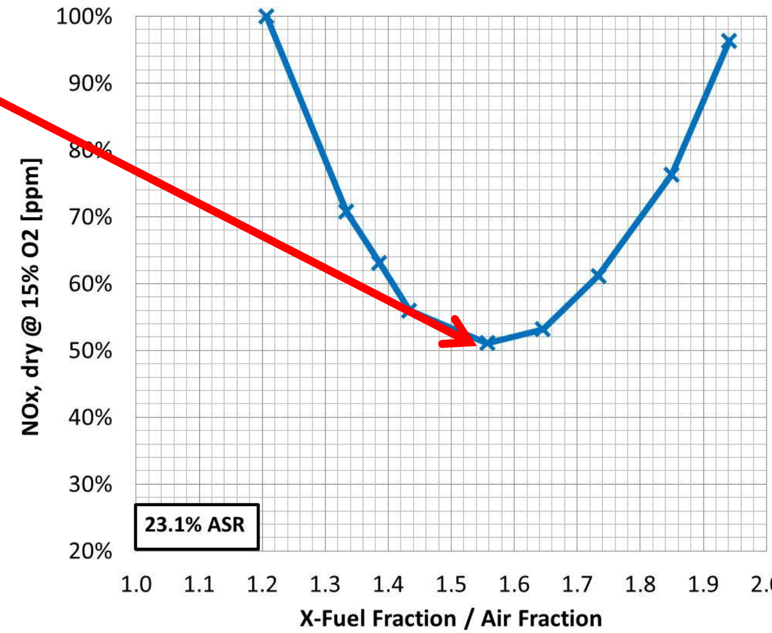
Increased Pre-Flame Entrainment Can Reduce NOx Emissions by more than 2X

Optimized Axial Stage Fuel Fraction Axial Stage Performs 55% Better than Primary Zone




Constant TIT Conditions

**Maximizing pre-flame entrainment of the cross flow combined with optimized X-stage fuel fraction leads to significant NOx reductions**

# *NOx Reduction Phenomena Utilized*

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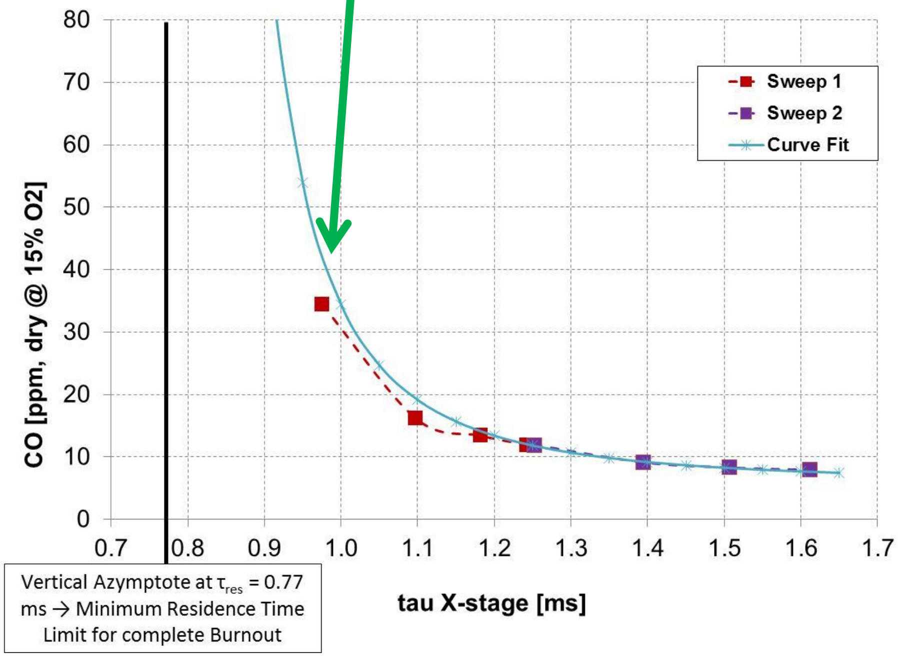
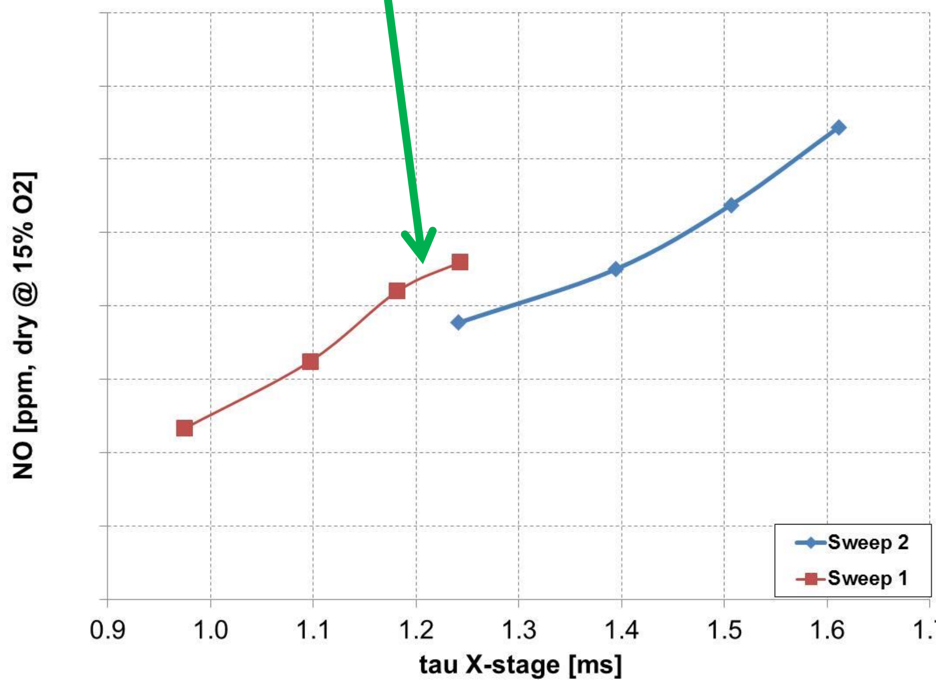
CO increases with decreasing residence time while NOx decreases → critical to identify minimum residence time




**A key enabler for low NOx emissions at high firing temperatures is to minimize the X-stage residence time – CO trend versus residence time used to determine residence time limit**

# *Demonstrated Results*

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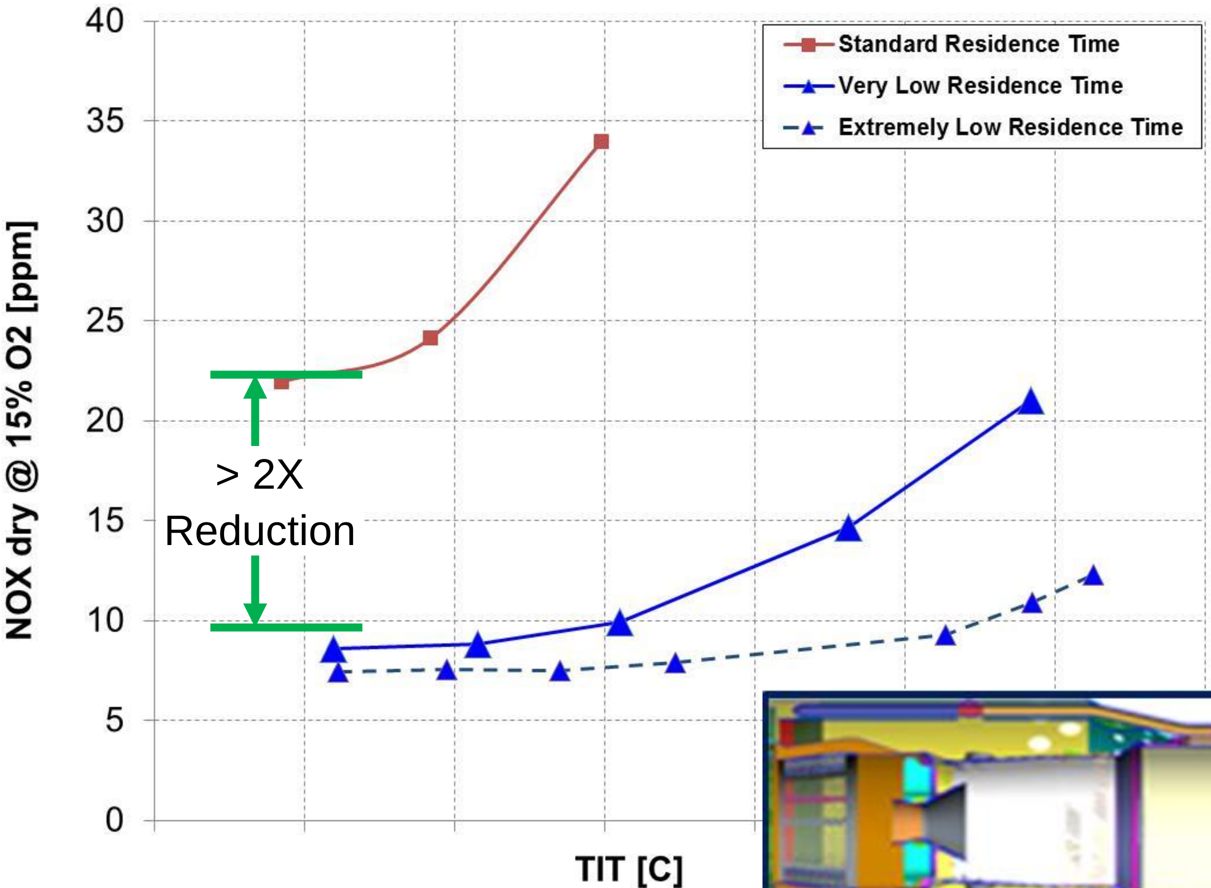


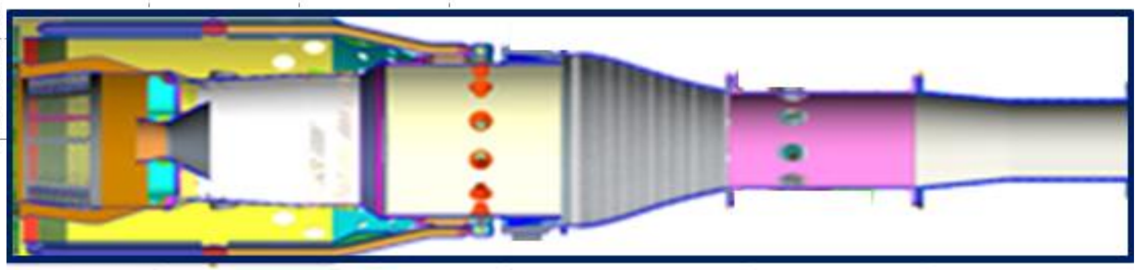

**NOx performance is better than the standard residence time system by over a factor of 2**

# *Future Work*

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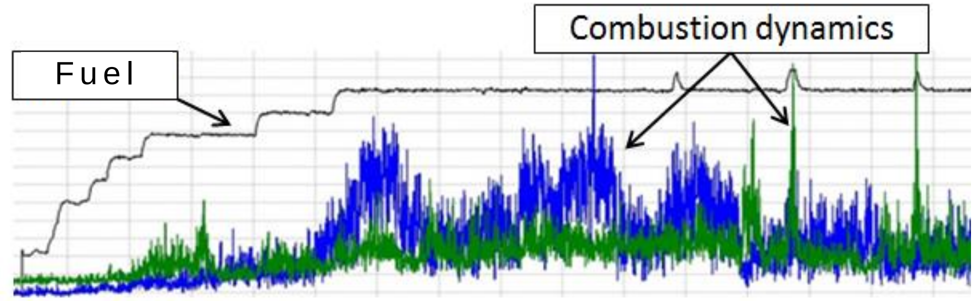
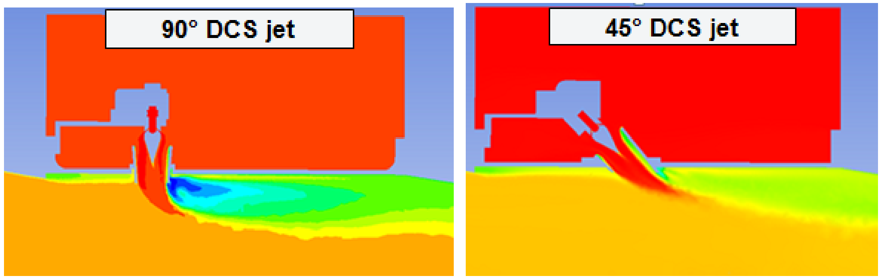
**Upcoming Milestones Prior to Engine Readiness:**

1. **High combustion dynamics when axial stage fuel nears optimum level**
2. **High pressure loss across axial stage flame**



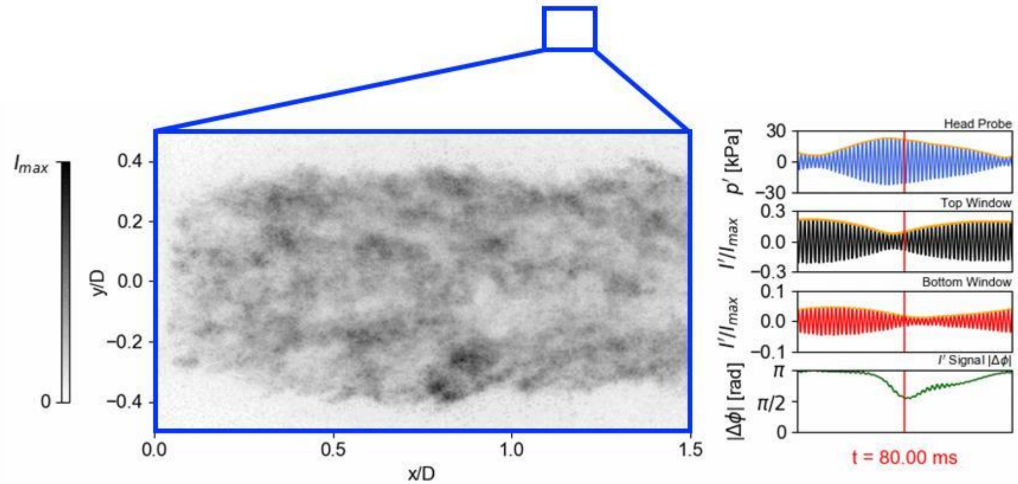

| | 90°Injectors | 45°Injectors |
|---|---|---|
| Total Pressure Drop | 10.5% | 7.9% |
| Static Pressure Drop | 30% | 27.2% |




**Remaining obstacles necessitate additional design variants for mitigation while maintaining high performance characteristics**

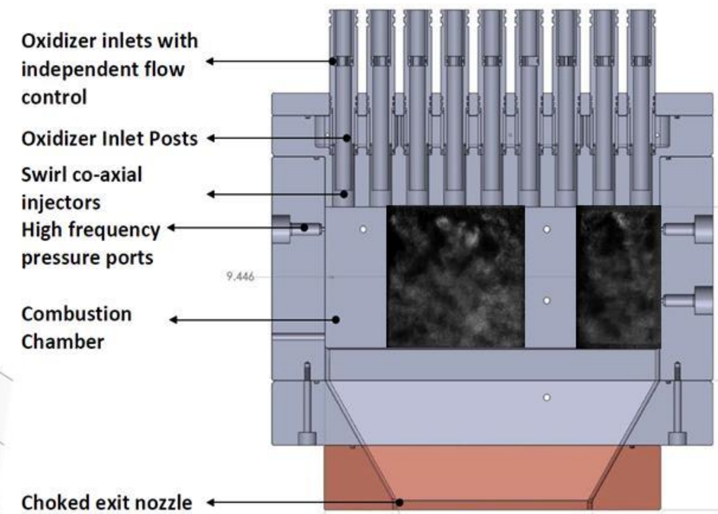
# Combustion Dynamics at High Power Density

## Self-Excited Instability Experiments at Purdue



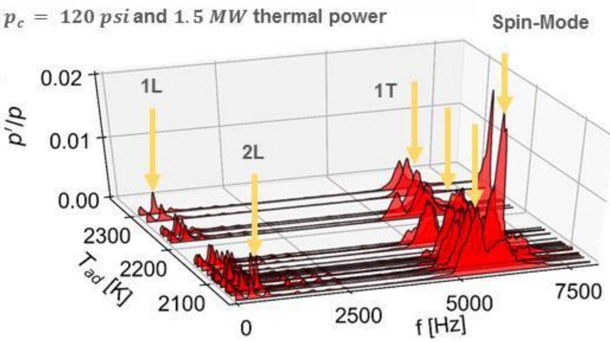

Single element, fully-premixed, air/methane flame at $p_c = 120\ psi$ and $1.5\ MW$ thermal power

- Multi-element rocket combustors have exhibited self-excited instabilities in array configurations
- Wide range of propellants, injector configurations, geometries, chamber pressures, instability amplitudes, and frequencies




9 element, O2/methane, swirl co-axial combustor ($p_C \approx$ 145 psi, 1T ≈ 2.6 kHz)

- Single-element combustors show three distinct instability regimes:
  - 1L instability ~370 Hz [p' = 0.8-1.3%]
  - Intermittent 1L and 1T instability behavior [p' = 2-6%]
  - Spinning instability [p' = 7-10%]



# Planned Approach

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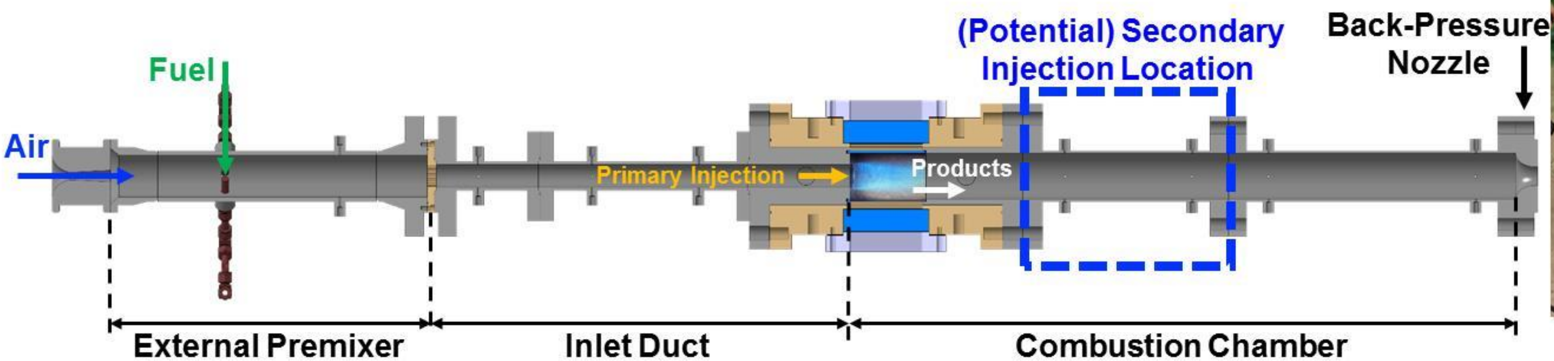
## Axially-Staged, High-Pressure Combustion Dynamics Experiment

- Objectives:
  - Develop an experiment to study combustion dynamics in a canonical staged combustion system, at engine-relevant flame conditions.
  - Replicate the complex instability coupling mechanisms that manifest intermediate and high-frequency dynamics with realistic acoustic and hydrodynamic scales
- Requirements:
  - 10 bar mean chamber pressure and 1-2 MW thermal power.
  - Hardware modularity to accommodate variation in 1) cross-flow Mach number at secondary injection, 2) Axial location of secondary injection, and 3) flow angle of secondary injection.
  - Diagnostics: dense array of high-frequency pressure transducers, high-speed chemiluminescence imaging (20-100 kHz), high-speed PIV (10-100 kHz), and high-speed PLIF (10-40 kHz)




# *Conclusions*

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1. The next generation axially staged combustion system has demonstrated the potential to enable 65% CC efficiency with < 25 ppm NOx
2. The NOx reduction is the result of high entrainment of the cross flow, minimum residence time, and optimization of air and fuel split to the axial stage
3. Future work is needed to reduce combustion induced thermoacoustics as well as to reduce the pressure losses introduced by the axial stage

# Thank You

# Questions?