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Rotating Detonation Combustion for Gas Turbines – Modeling and System Synthesis to Exceed 65% Efficiency Goal

DE-FE0023983

Scott Claflin, Director, Power Innovations

University Turbine Systems Research annual meeting
Daytona Beach, FL Oct 30 – Nov 1, 2018

Acknowledgement

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Robin Ames
Program Manager - NETL

Ken Sprouse
Principle Investigator – Systems Development

Jeffrey Stout
Project Engineer – Combustion Devices

Edward D. Lynch
Fellow – Combustion CFD

Alan Darby
Program Manager – Power Innovations

Objective of Program

To advance combustion turbine technologies for combined cycle applications…

…by integrating a Rotating Detonation Engine (RDE), pressure gain combustion system with an air-breathing power-generating turbine system to achieve a combined cycle efficiency equal to or greater than 65%.

RDE Phase II Program Overview

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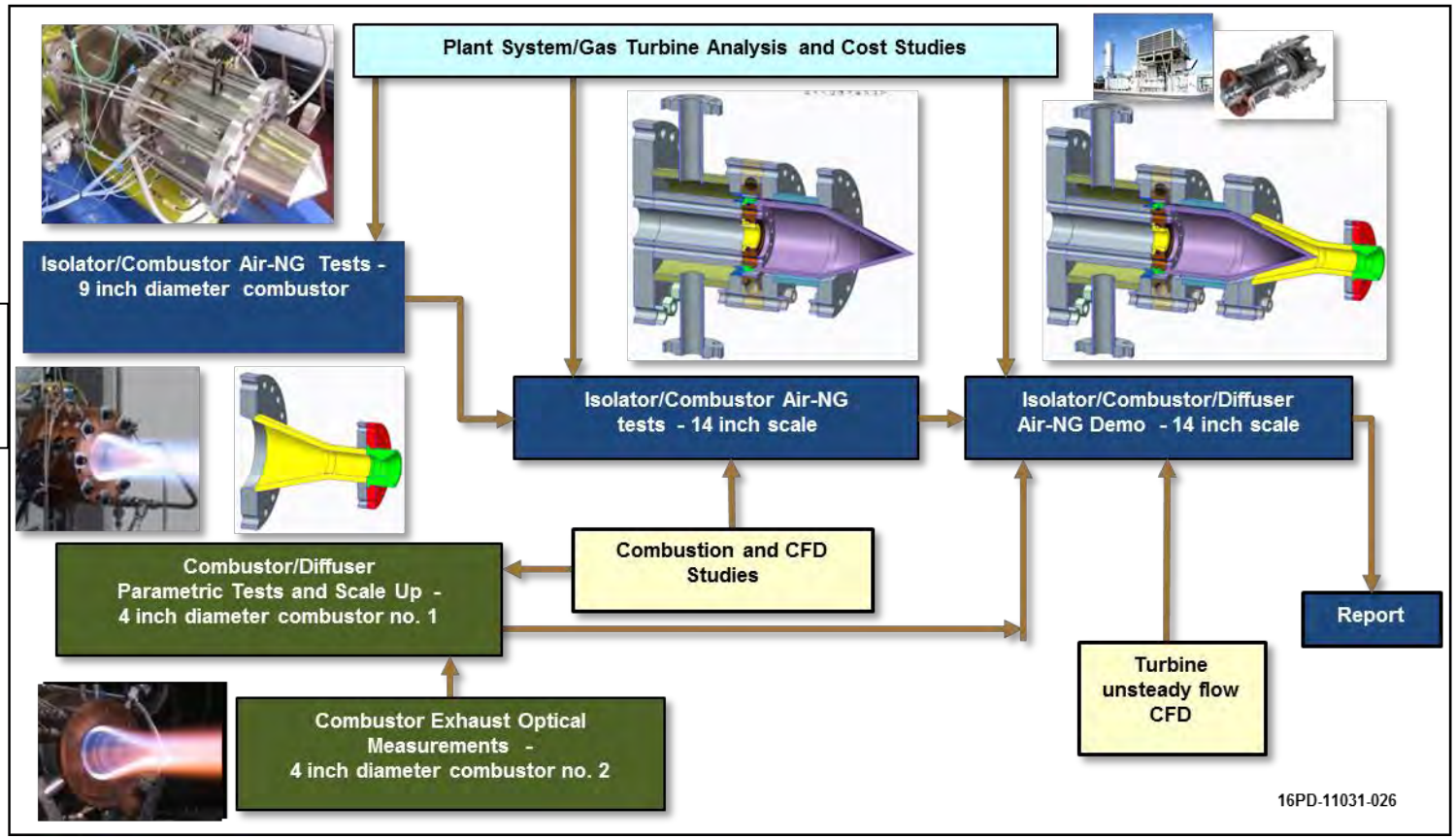
Advance Pressure Gain Combustion Technology for Turbine Applications

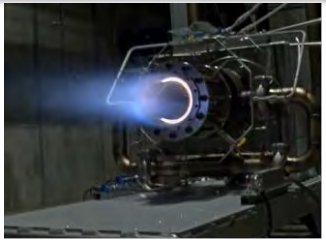
Component Design, Test, Performance Data → **Integrated Component Design And Test** → **Power Plant Study**

- **Existing Hardware**
- **Separate Test Sites**

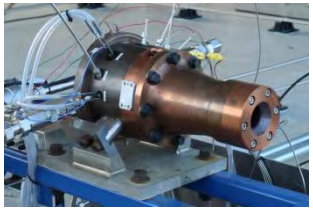


Rotating Detonation Combustion for Gas Turbines Program Elements

Aerojet Rocketdyne
- Project lead & system integrator

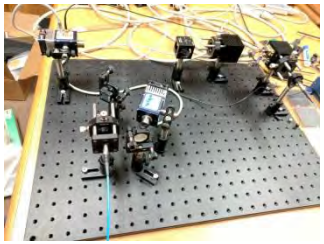


Purdue University
- Flow effects on turbine efficiency
- 21-cm and 31-cm RDE testing with air/natural gas.



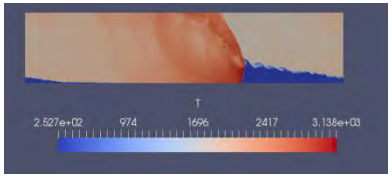
Southwest Research Institute
- Testing 10-cm RDE and various diffuser geometries with optical diagnostics

University of Alabama
- Testing 10-cm RDE with optical diagnostics for combustor & diffuser exhaust flow characterization.



University of Central Florida
- High fidelity TDLAS optical diagnostic for composition & unsteady flow analysis

University of Michigan
- Lab-scale testing and CFD modeling of RDE for injector & combustion physics



Duke Energy
- NGCC integrated plant study support and funding partner

RDE Design Problem Statement

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Sources of Significant Pressure Loss

ISOLATOR/INJECTOR

- Reduce upstream pressure fluctuations
- Various devices shown to be effective
- Prior program demonstrated <20% Pt loss, and peak oscillation

RDE COMBUSTOR*

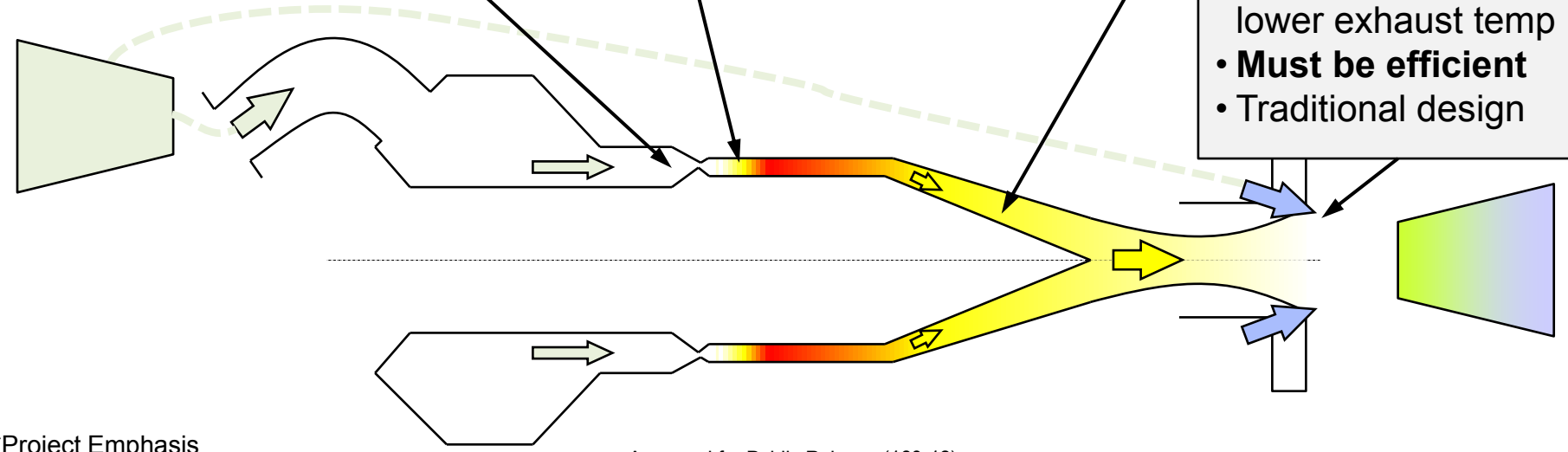
- Air/NG detonation difficult due to large cell size (300mm @ STP)
- Requires large combustor
- Injection, mixing significant

DIFFUSER*

- Primary focus of Phase I, II program
- Reduce downstream pressure fluctuations
- Minimal total pressure loss

BYPASS MIXER

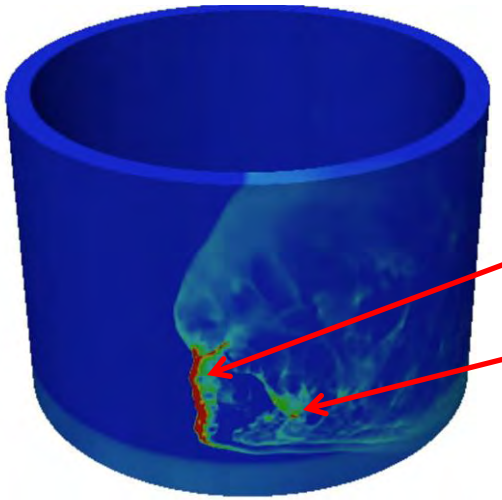
- May be req'd to lower exhaust temp
- **Must be efficient**
- Traditional design



*Project Emphasis

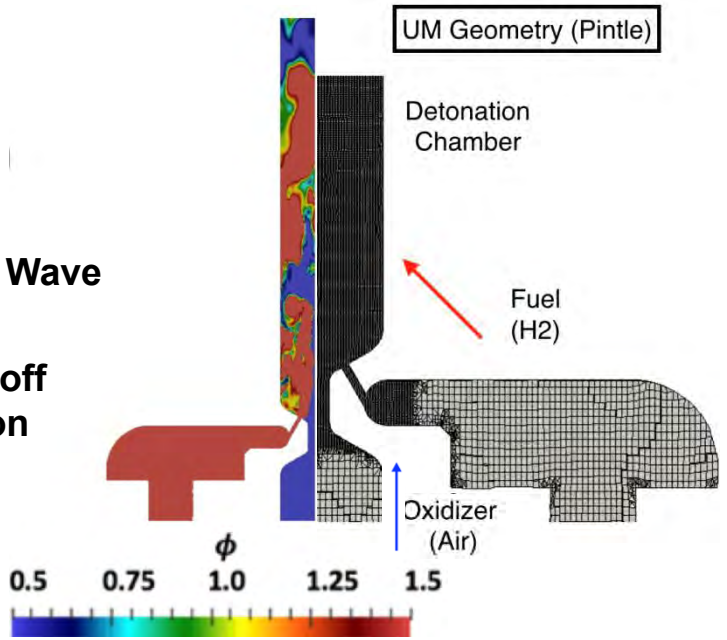
UM CFD Completed for Pintle Configuration

Instantaneous Pressure



- Geometry Similar to AR Geometry with More Constriction and Larger Base Separation
- Large Eddy Simulation with Finite-Rate Chemistry

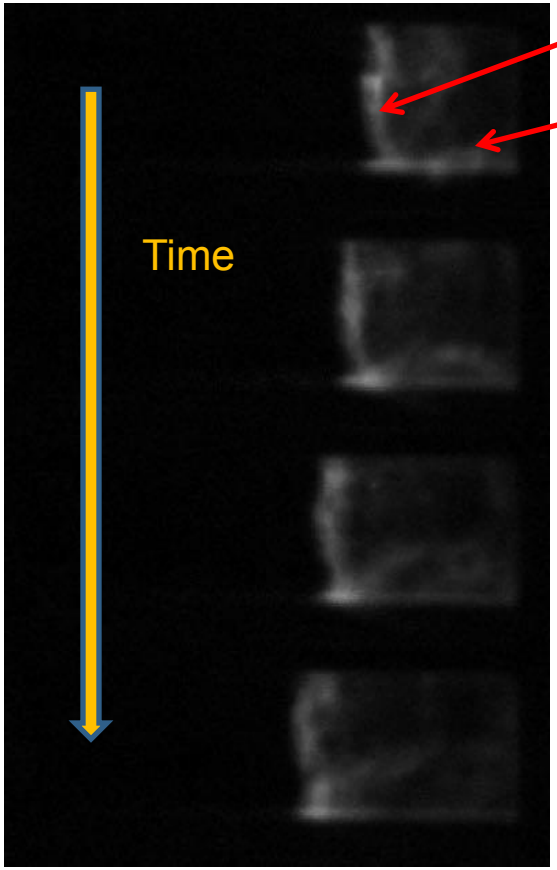
Instantaneous Fuel Equivalence Ratio



- 17% Pressure Oscillations in Airstream Upstream of Constriction
- Total Pressure Computed at Exit; Being Extended to Axial Planes Down Combustor
- Implications for Total Pressure Loss in "Isolator," Penetration and Mixing from Injector in Annulus

Flow Visualization for RT-RDE (Oval Racetrack) Underway for Pintle Configuration

Chemiluminescence from Side

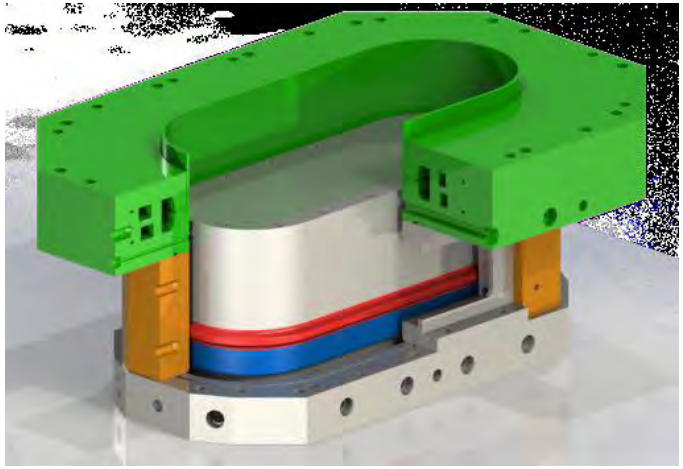


Detonation Wave

Reflection off Constriction

- **Racetrack in Operation for Pintle (AR-Like Config)**
- **Compared to Round RDE Operation; Generally Similar but with Some Differences**
- **Initial Diagnostics Performed; Appear to Resemble CFD for Same Configuration**

Wave Speed: speeds are approximately 80 m/s slower than equivalent round RDE wave.

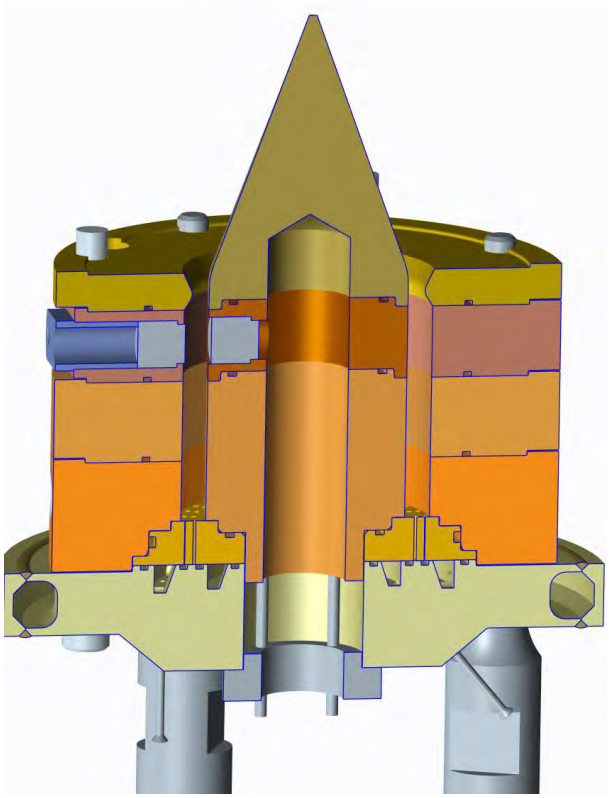


- **Chemiluminescence**
- **Double pass Schlieren**
- **Combined Acetone, OH, Toluene PLIF in Combustor in Planes**
- **Line of Sight Absorption Measurements of Key Combustor Species—H2O**
- **Gas Sampling of Species at Exit—NOX**

Test Site	Hot-Fire Tally	Purpose
University of Michigan (Ø6” RDE: Air+H2)	> 30 attempts > 17 with detonation	Obtain Optical Hot-fire Injector/Combustion Chamber Data

University of Alabama – Particle Image Velocimetry

Test Site	Hot-Fire Tally	Purpose
University of Alabama (Ø4” RDE: O2+CH4) 4 configurations with 2 diffusers	85 attempts 83 with detonation 47 with PIV	Performance Testing with SOTA Optical Techniques (PIV and Chemiluminescence)



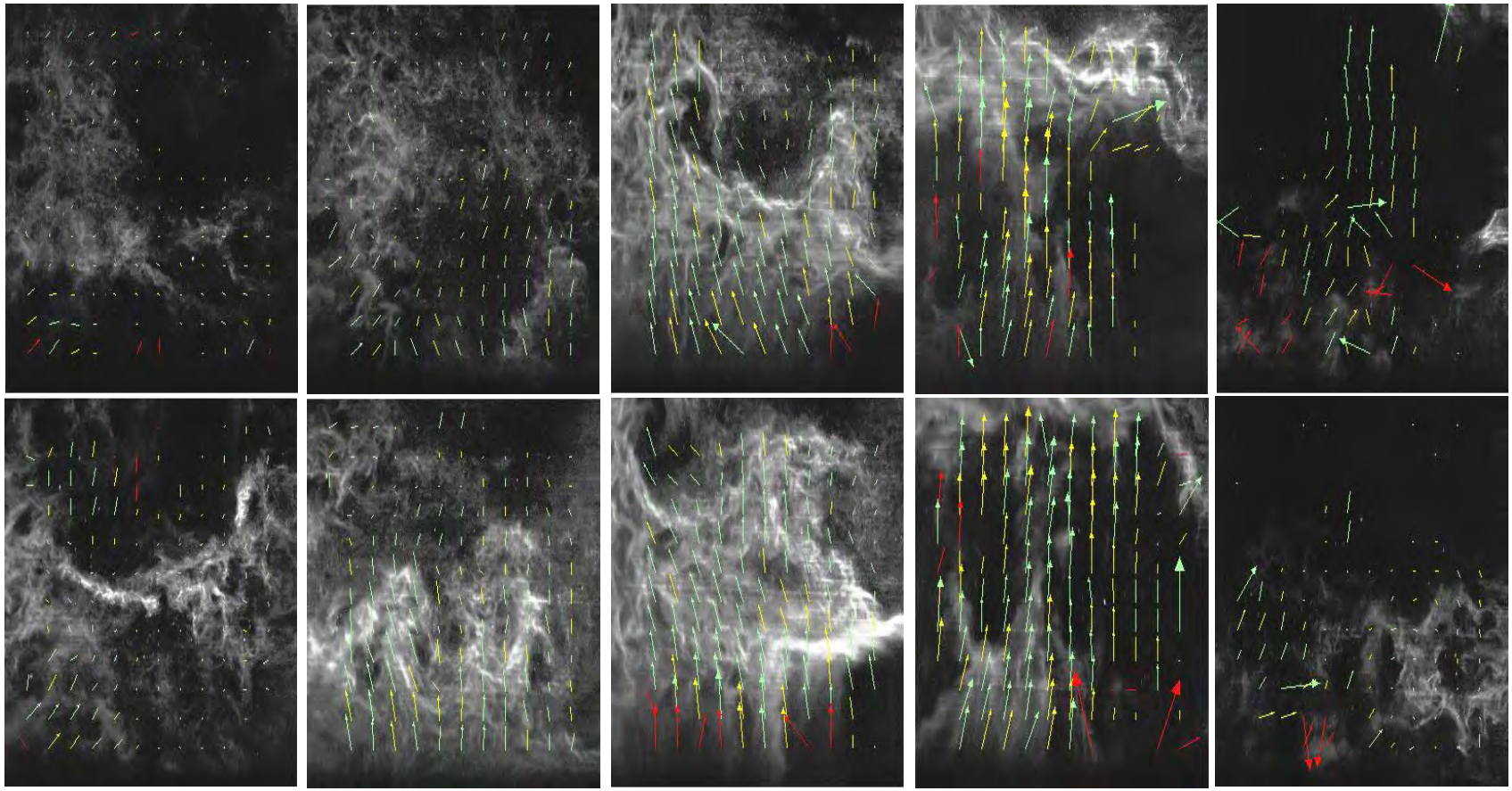
Previous testing with PIV diagnostics used 30kHz laser/camera.

New laser will allow 100kHz

Particle Imaging Results at 0.06 Millisecond Intervals

0.354
(image 6018)

0.35424
(image 6022)



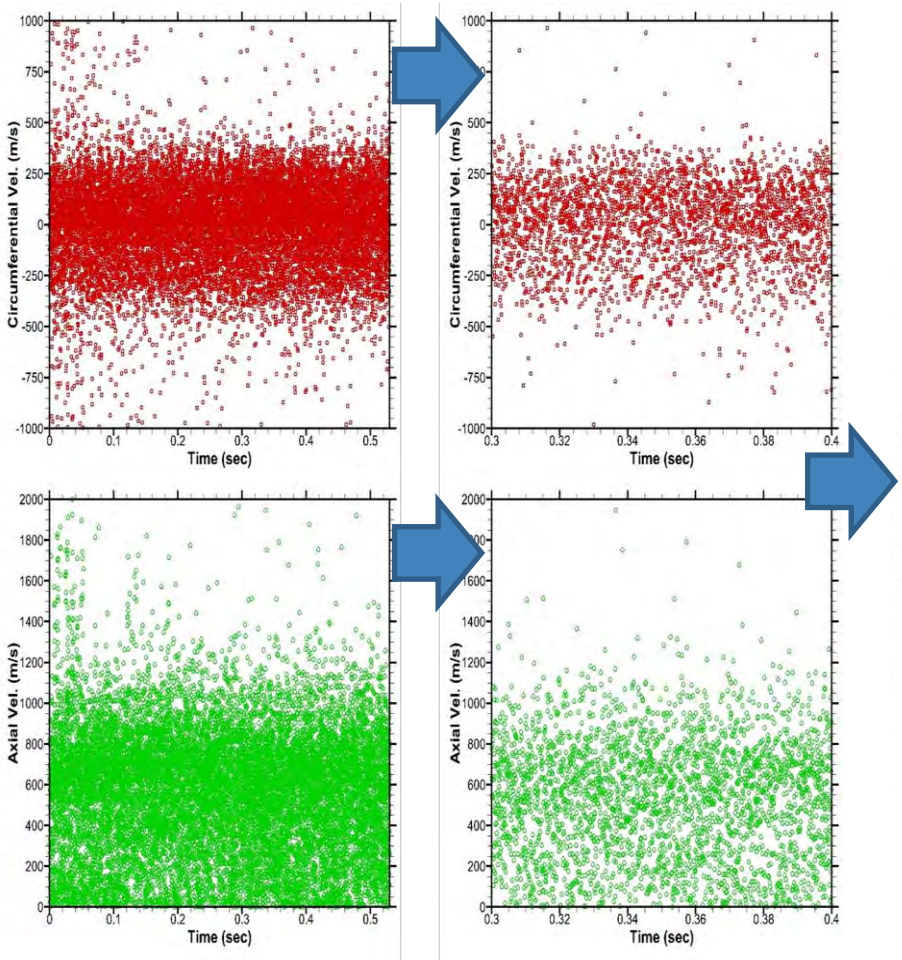
0.35429
(image 6023)

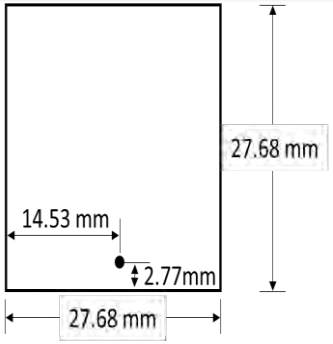
0.35453
(image 6027)

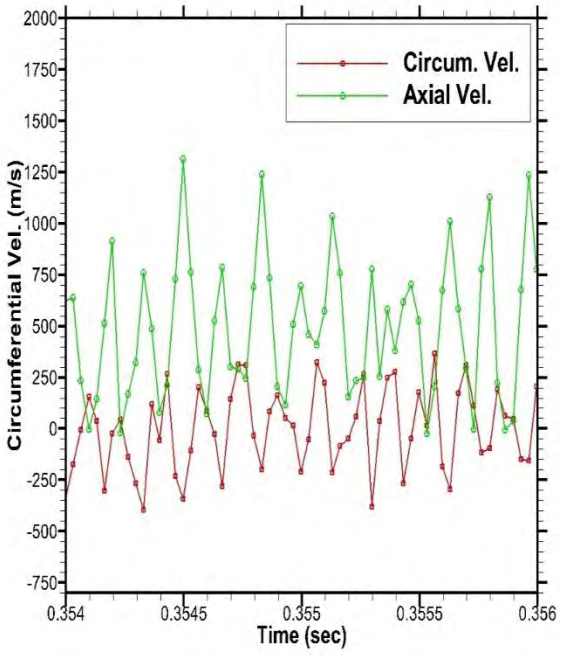
PIV Analysis: Recap of Previous Work

Entire Data Set

Narrow Time Slice

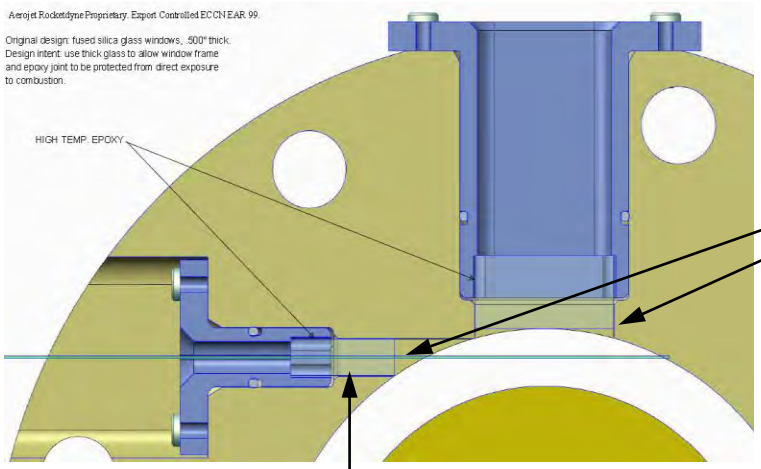






- Single point analysis; point chosen in center of image and close to annulus exit
- >16000 consecutive images yielding PIV data
- When time range was reduced, cyclical trends became apparent

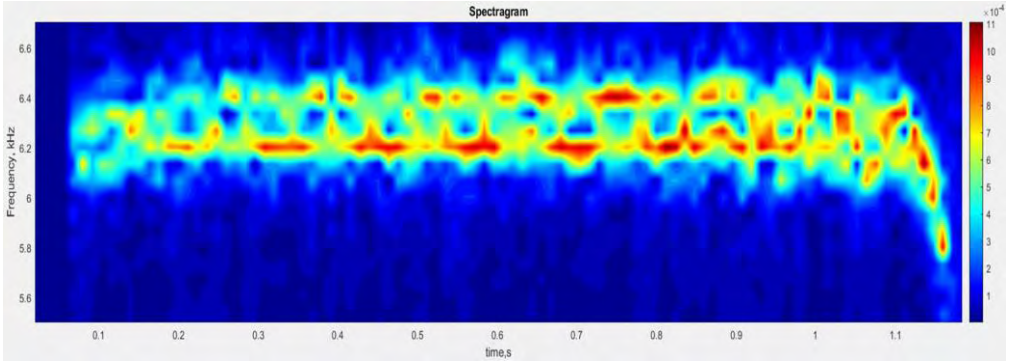
Recent Progress – PIV Upgrades



Upgrade PIV camera and laser windows to sapphire to allow in-chamber velocimetry
To be tested October 2018

Parallelogram window shape eliminates recirculation zone

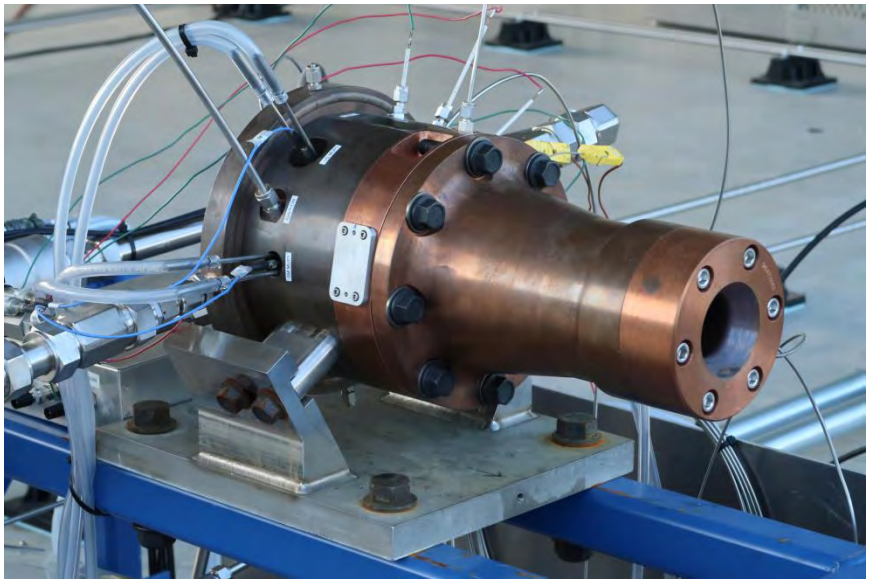
Improvements to analytical tools for high frequency data (pressure, ion probes)



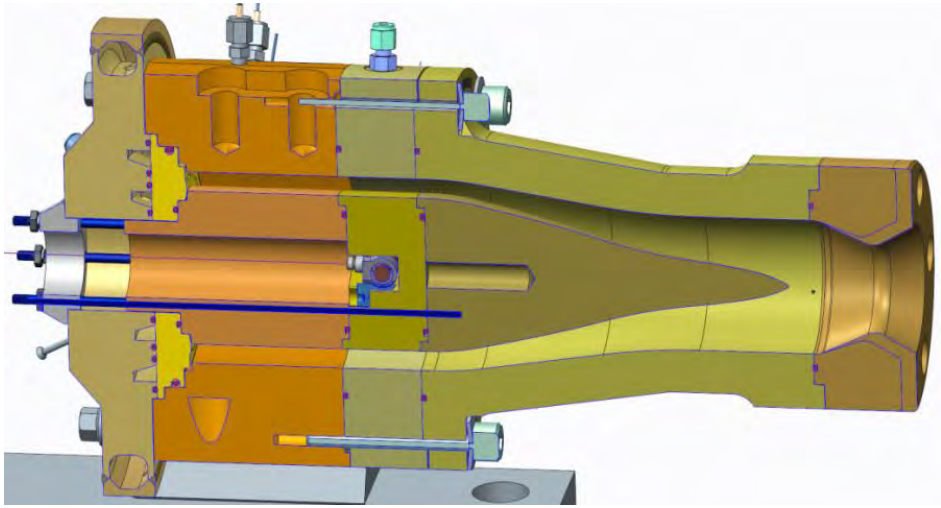
Spectrogram from high frequency data.

Diffuser Risk Reduction
Southwest Research Institute

- Tested diffuser configurations for design/performance data using advanced optical diagnostics from the University of Central Florida
- Used existing Aerojet Rocketdyne 4-inch RDE at SwRI
- Operated on hydrogen and slightly enriched air

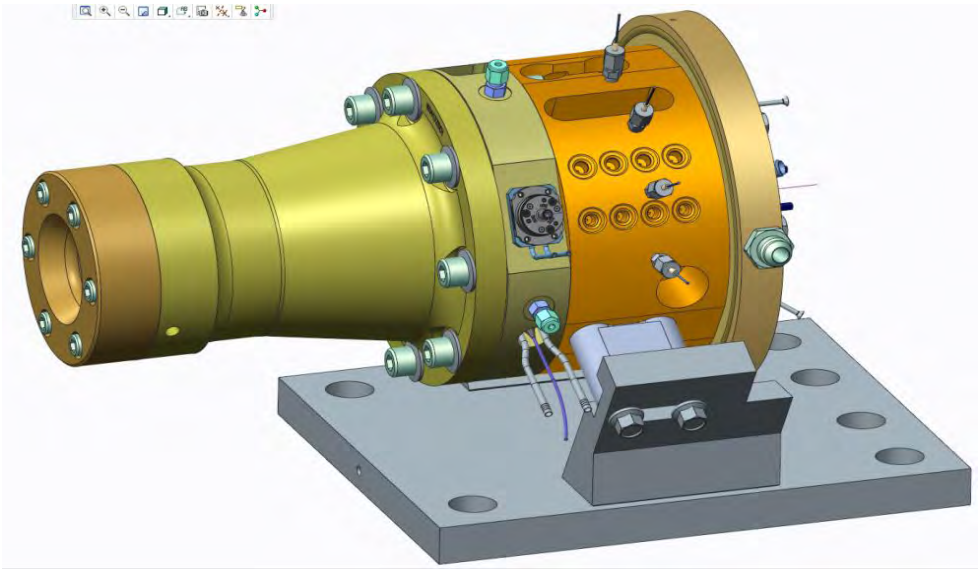


AR 4-inch RDE installed at SwRI facility with diffuser

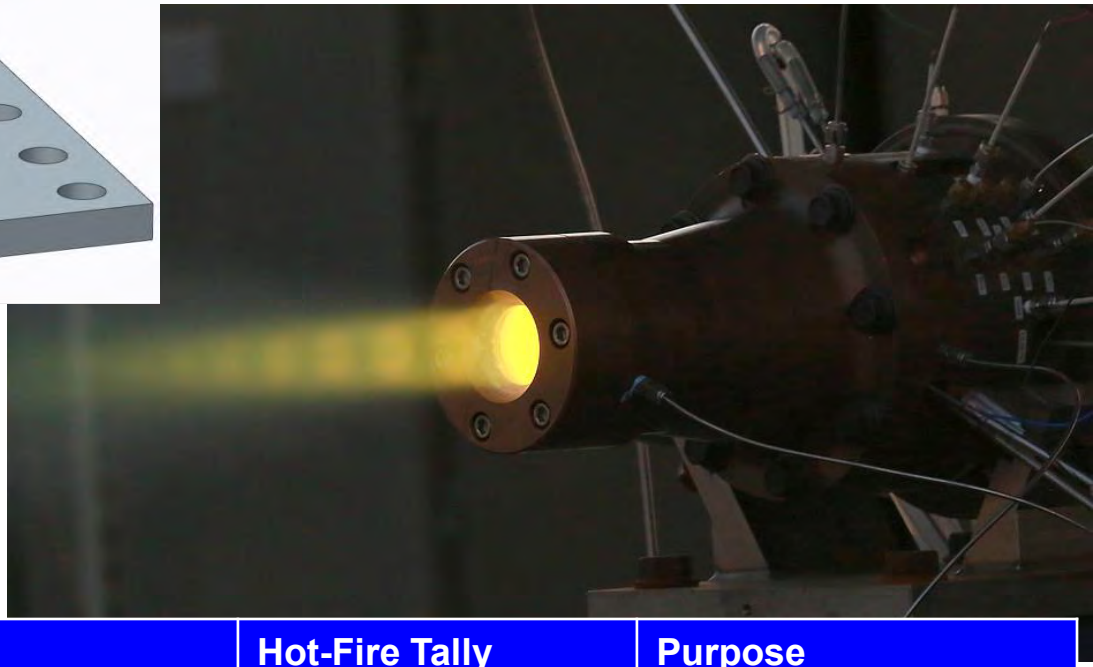


Added modular optical spools and diffuser variants

SwRI Diffuser Test Layout & Geometry



- Combustion Annulus: 4 .0” OD x 3.15” ID
  - Diffuser Geometry: Diffuser #2
- Operating Conditions
  - Air/Hydrogen at approximately 1 lb/sec
  - Chamber pressure approximately 50 psia
  - Exit pressure: 14.7 psia

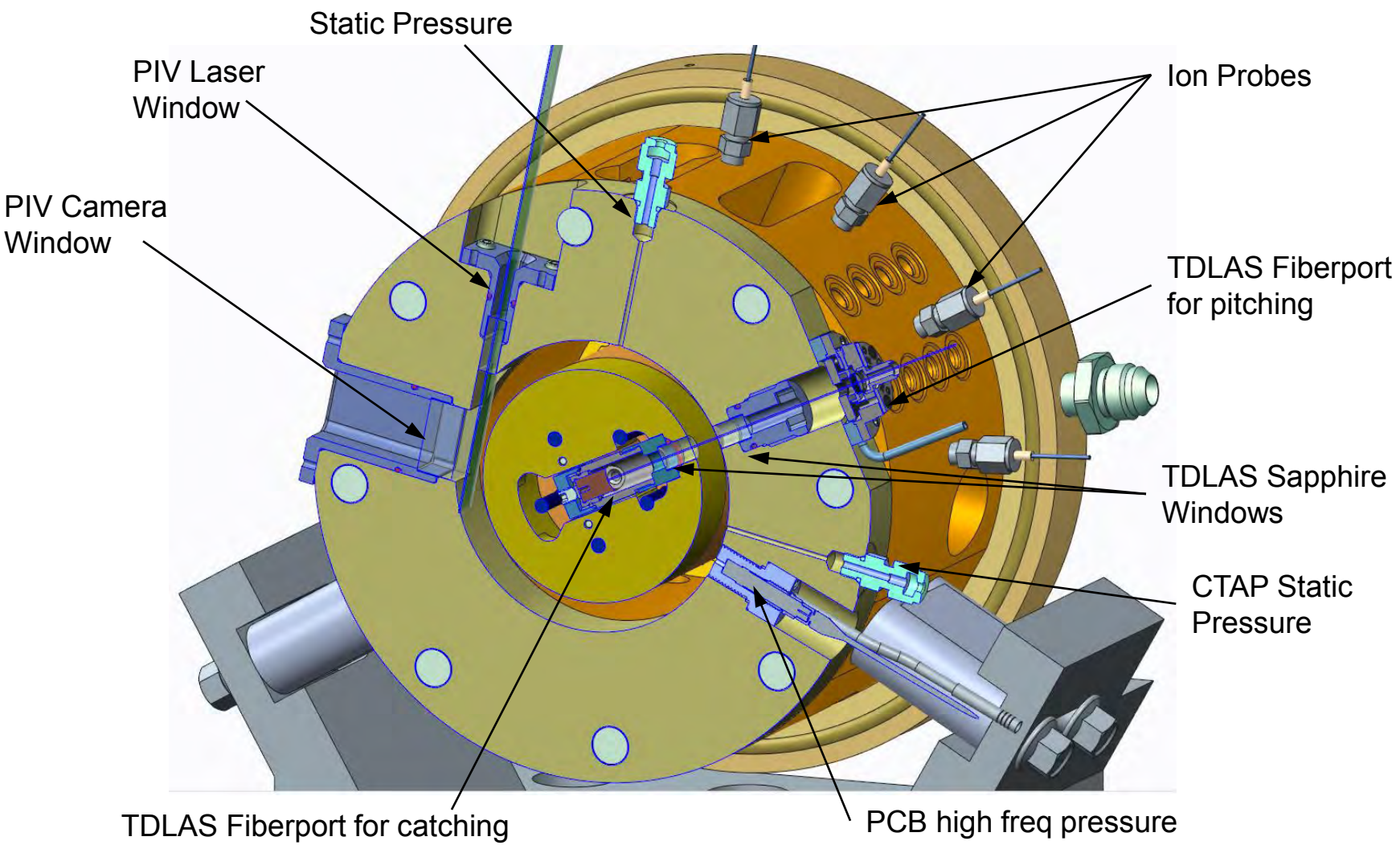


RDE was highly instrumented with:

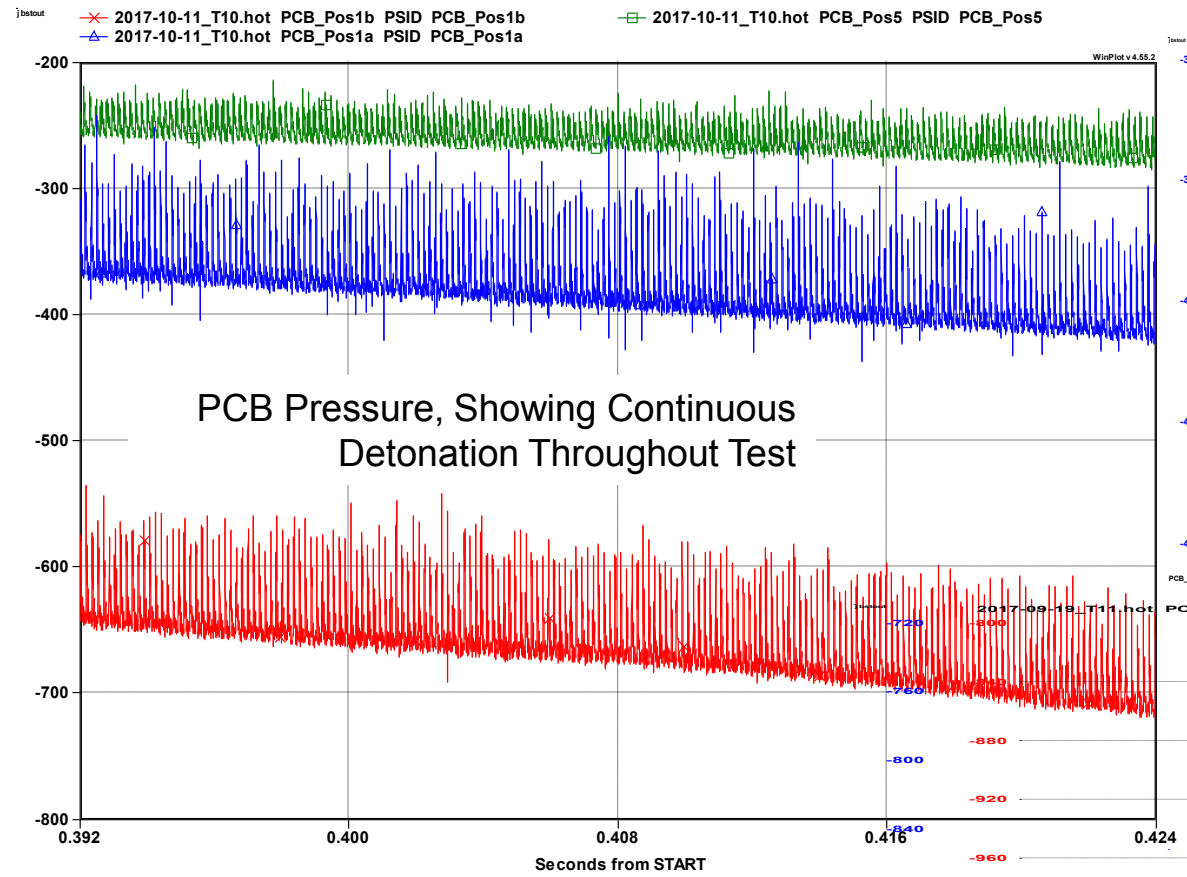
- 4x ion gauges
- 3x PCB high frequency pressure sensors in water cooled jackets
- 3x static pressure
- 3x static pressure, CTAP
- Sapphire windows for TDLAS
- Quartz windows for PIV

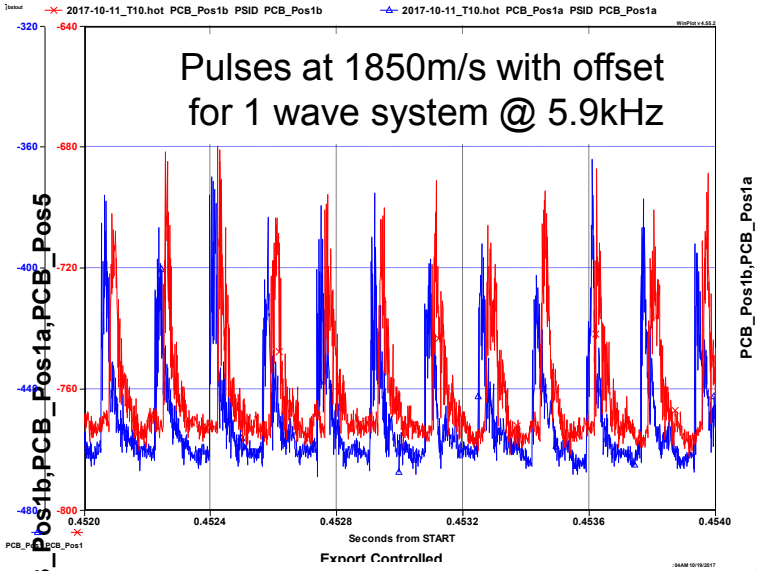
Test Site	Hot-Fire Tally	Purpose
Southwest Research Institute (Ø4” RDE: Air+H2) 3 diffusers	200 attempts 142 with detonation 15 with TDLAS 66 with PIV	Diffuser Performance Evaluation with TDLAS

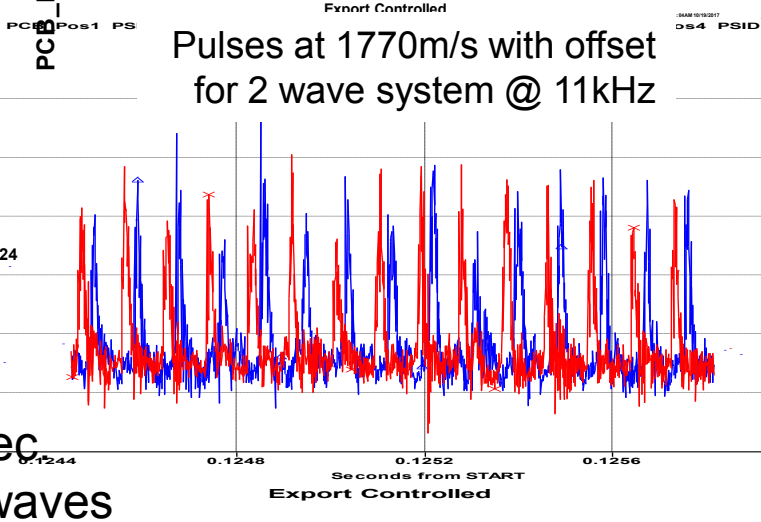
Diagnostic Access Spool for 4-inch RDE at SwRI



Quality High Frequency Data



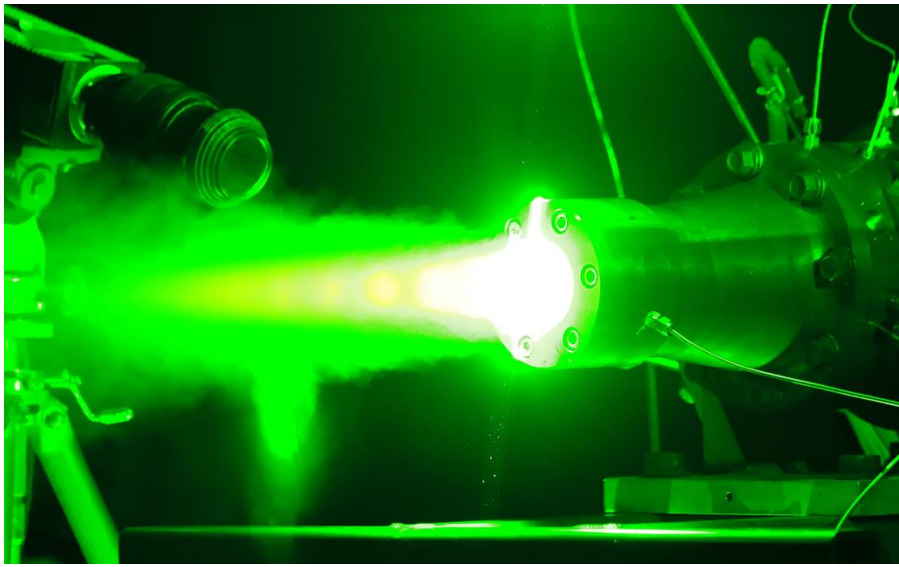




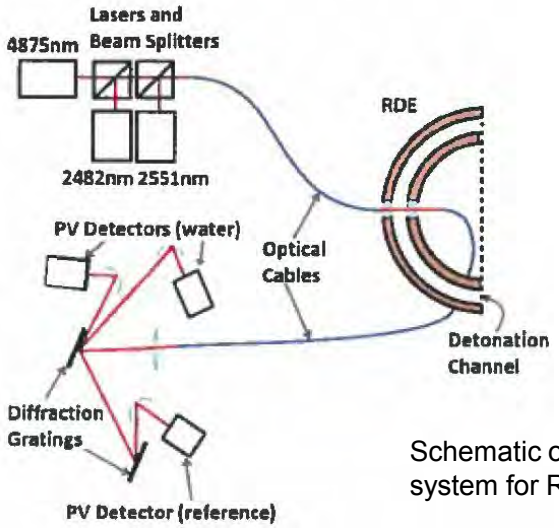
- 85 Tests with continuous detonation
- All tests with PCB pressure at 1M samples/sec.
- 23 Tests with TDLAS measuring at 2M samples/sec.
  - TDLAS able to characterize individual shockwaves

RDE Test Diagnostics, University of Central Florida

- **Provided PIV diagnostics for SwRI test series, Dec 2017**
- **Conducted Tunable Diode Laser Absorption Spectroscopy (TDLAS) measurements/diagnostics on 4" RDE at both UofA and SwRI, Oct-Dec 2017**
- **TDLAS System capable of measuring CO (4.58um), CO2 (4.25um), water (2.48um & 2.55um), and temperature, at 2MHz.**
- **Setup at SwRI & UA in 2017 had many challenges, mostly due to high vibration environment**
- **Making improvements for October 2018 test series at UA**



UCF Laser and high speed camera characterizing RDE diffuser exhaust at SwRI test facility



Schematic of TDLAS system for RDE

University Of Central Florida

After Initial Transients CFD Static T Corresponds to TDLAS Measurement: Total T Suggest Pressure Gain

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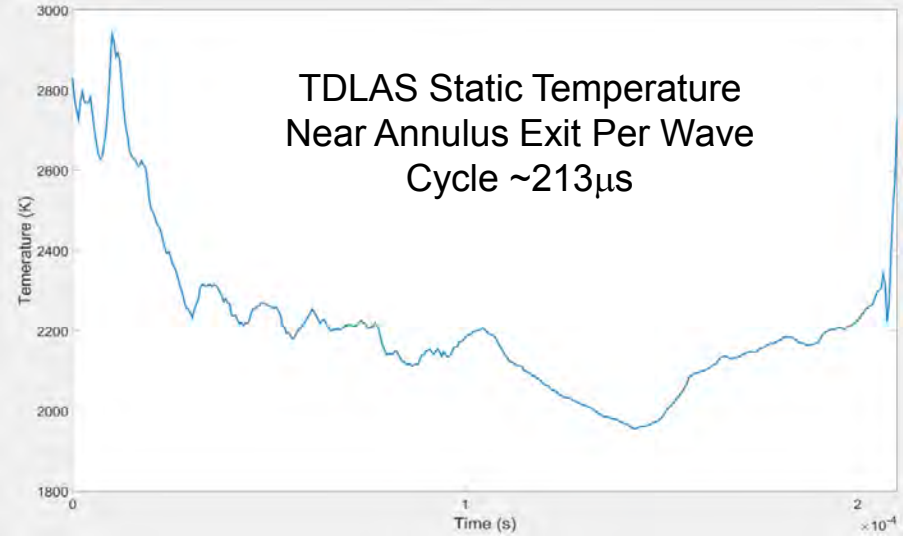

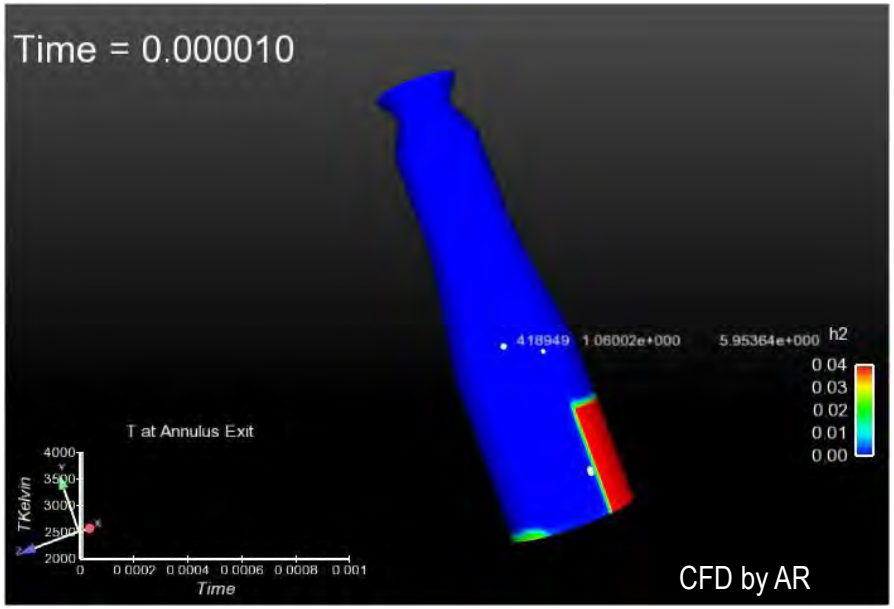

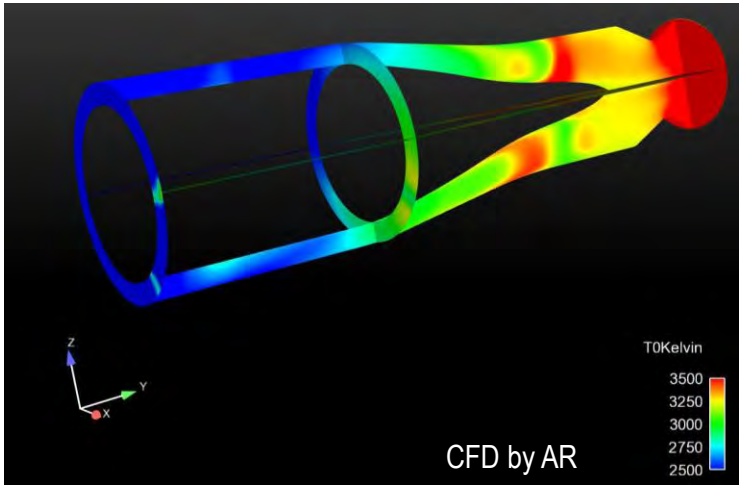

Improvements Targeted at Increased SNR and Tolerance of Vibration - For Oct 2018 Test @ UA

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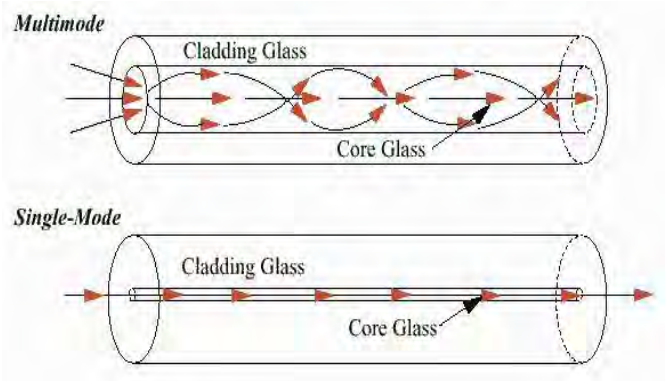
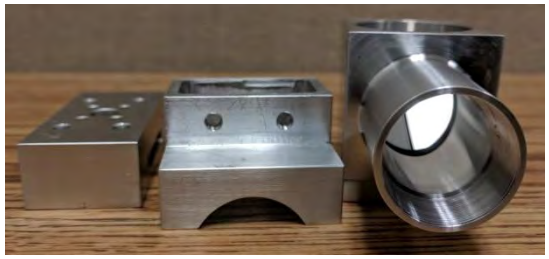
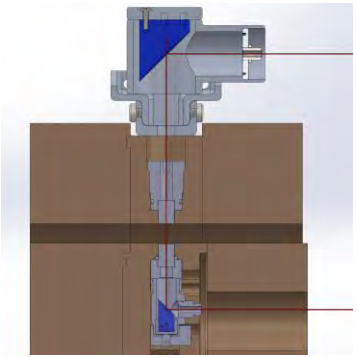


- Change fiber type from multimode to single-mode
  - will reduce noise from birefringence and modal noise.





- Minimizing Beam Steering with Larger Optics
  - New custom optics adapter for direct mount on RDE diagnostic spool

- Mitigating Transmission of Vibration to Instrument
  - Passive damping mounts
  - Acoustic foam

Air + Natural Gas RDE Operation Demonstrated with AR 9.4-inch RDE

Test Site	Hot-Fire Tally	Purpose
Nov2017 (Ø9.4" RDE: Air+NG) 2 injectors, 2 backpressure nozzles	41 attempts 21 with detonation	NG/Air Performance Testing
May2018 (Ø9.4" RDE: Air+NG) 2 injectors, 3 backpressure nozzles	86 attempts 54 with detonation	NG/Air Performance Testing (characterize exhaust with SOTA-PIV)

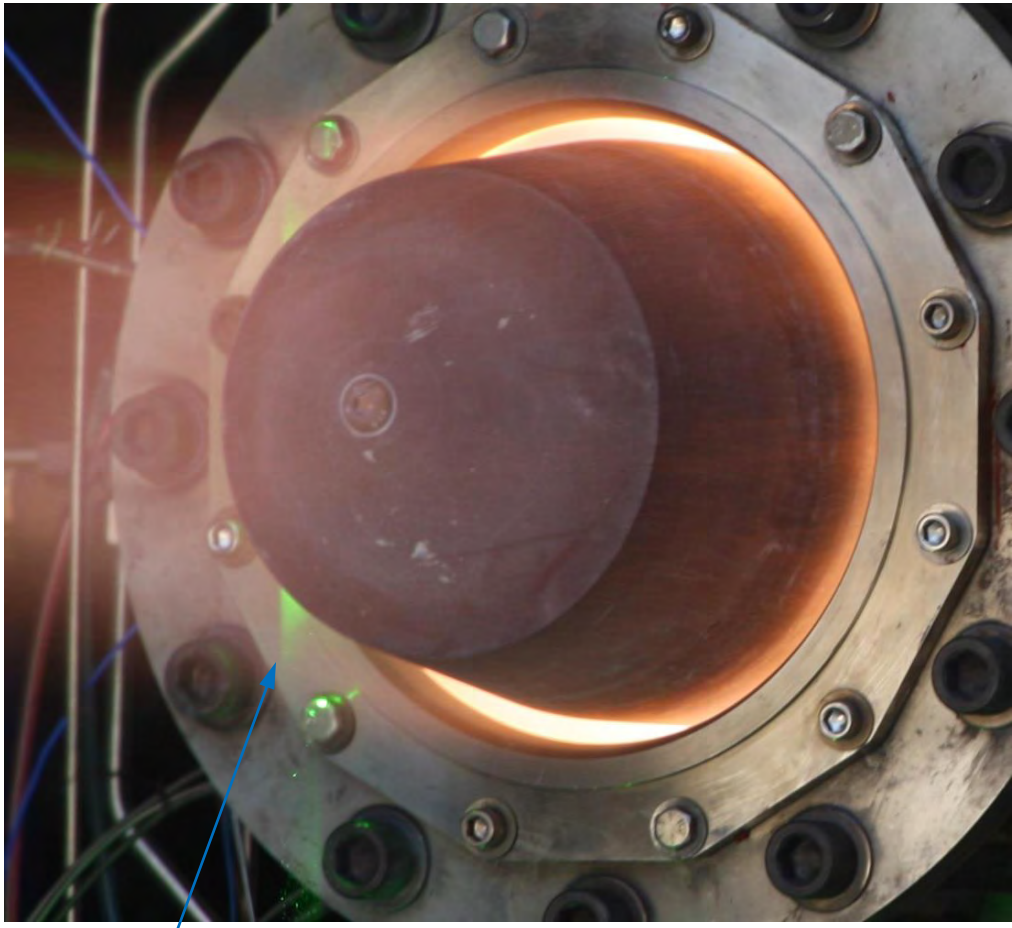
APEX Test Stand w/ AR 9.4" RDE Installed

<u>9.4" RDE Operational Extents (May 2018)</u>
Air Flow: 1.1 to 11.8 Lb/s
Air Temp: 484°F – 810°F
Equiv ratio, ϕ,: 0.87 to 1.15
Air O2 fraction: 21%-33%
Total Mass flux: 50-556 kg/m^2/sec

<u>9.4" RDE Detonation Observations (May2018)</u>
- Tests with no supplemental O2: all slapping mode, < 1200m/s
- Observed a few tests with one-directional waves > 1800m/s
- Requires larger RDE to demonstrate air+NG without supplemental oxygen

PIV Setup for 9.4” RDE

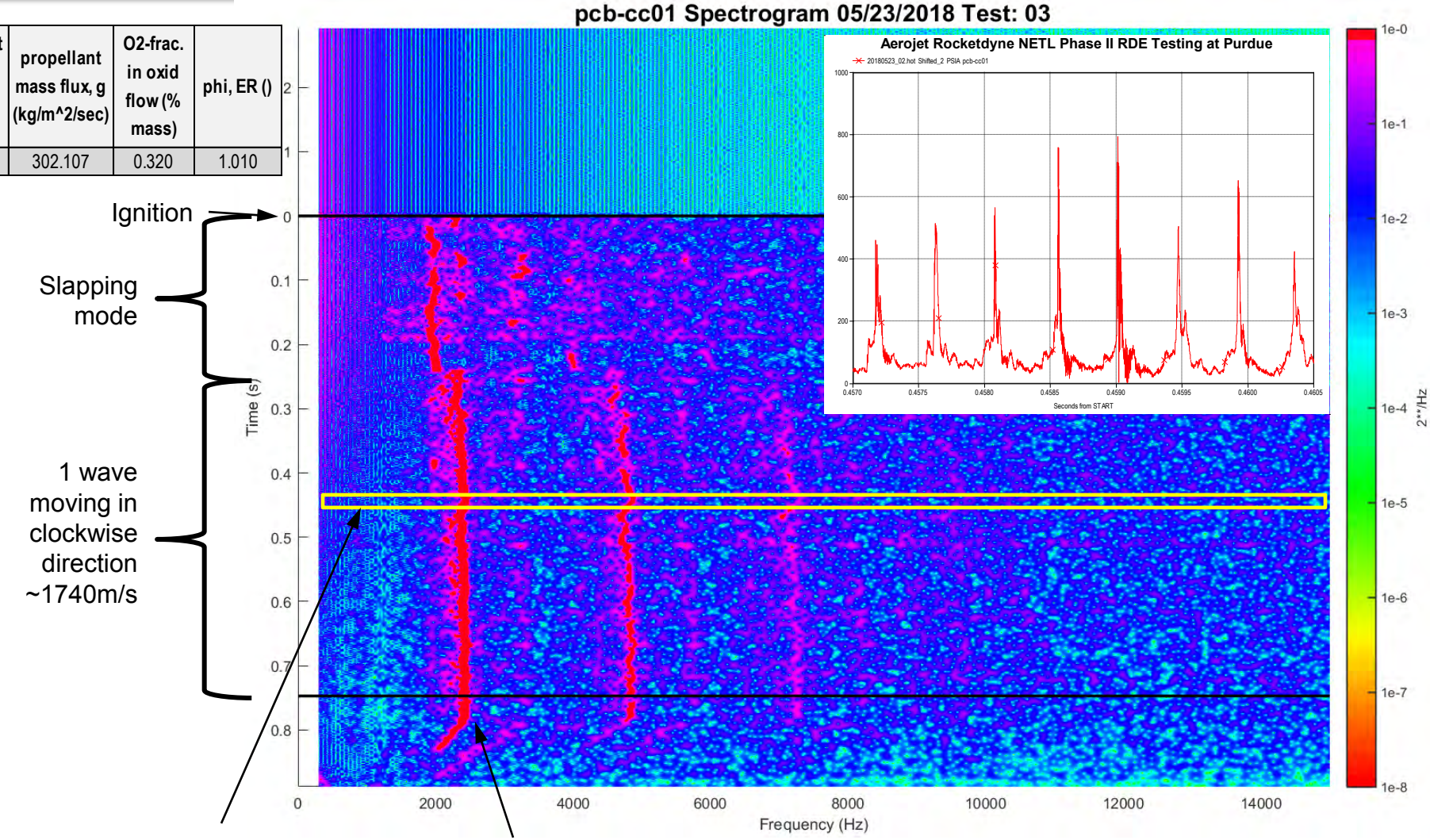
- Laser pulse-pair doublet frequency: 102.5 kHz
  - Velocity Time Series Spacing: 9.75 µs
- Temporal Resolution (Pulse-Pair Delta): 200 ns
  - Light Pulse Illuminating Duration: 5 ns
  - Light Pulse Energy: 400 mJ
- Burst Duration: 10 ms
  - Followed by 1 second cool down period
- Camera speed: 205 kHz
  - Two frames for each pulse-pair doublet
- Camera’s Active Sensor Grid: 256 x 256 pixels
- Spatial Resolution: 99 µm/pixel
- Velocity Vector Spacing: 0.59 mm



SLR photo captured laser sheet pulse (on backside of centerbody)

Spectrogram of High Frequency Pressure Data

propellant total flowrate (lbm/sec)	propellant mass flux, g (kg/m^2/sec)	O2-frac. in oxid flow (% mass)	phi, ER ()
7.128	302.107	0.320	1.010



Purdue University

Measured Seed Particle Velocities at 100kHz PIV Vector Components, 2018-05-23_Test03

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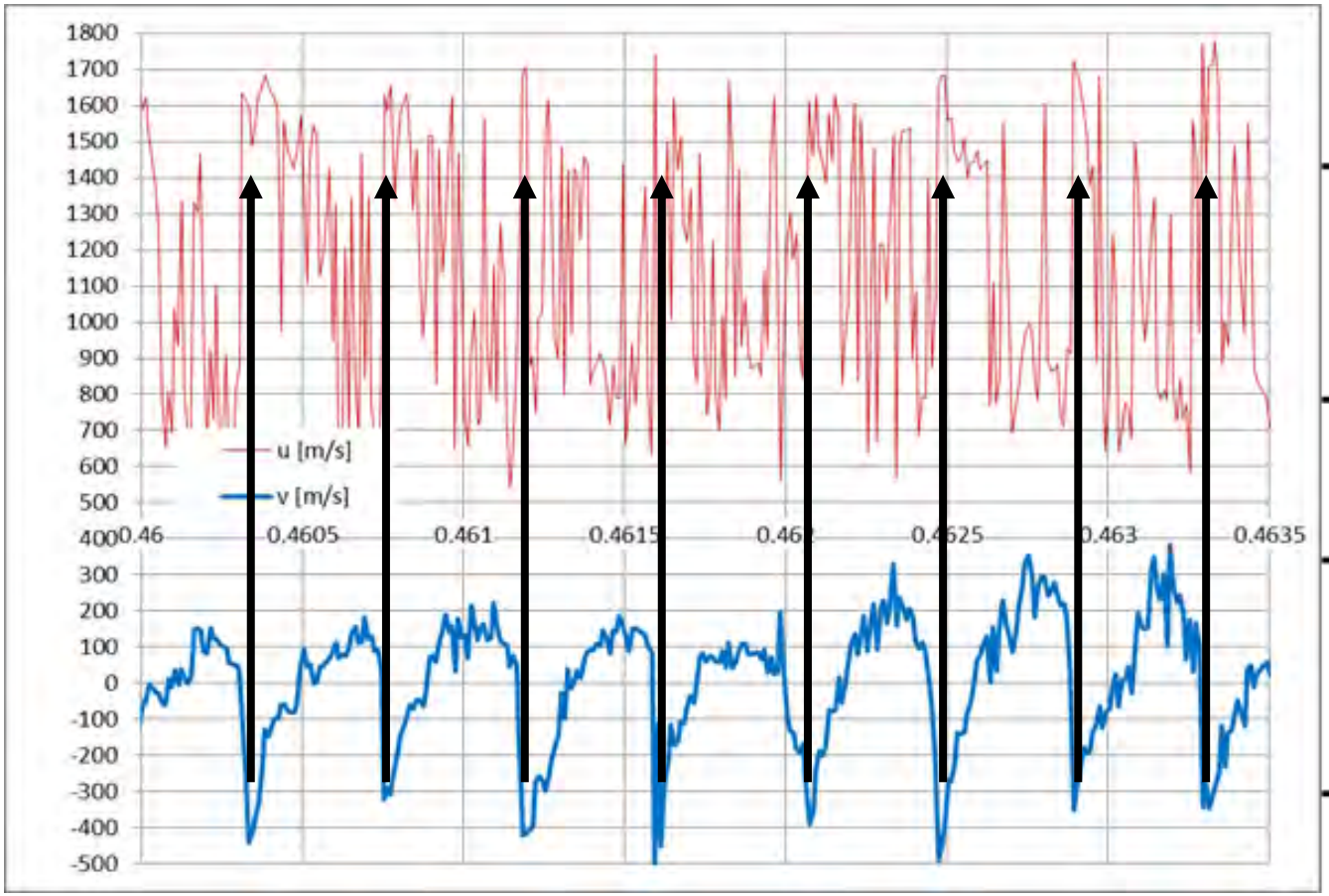

Axial Component

Tangential Component

Wave shape indicates counter-clockwise wave rotation

Purdue 200kHz system provided unprecedented temporal resolution, allows over 40 samples per 430μs detonation cycle.

Purdue University

Measured Seed Particle Velocities at 100kHz PIV Vector Components, 2018-05-23_Test06

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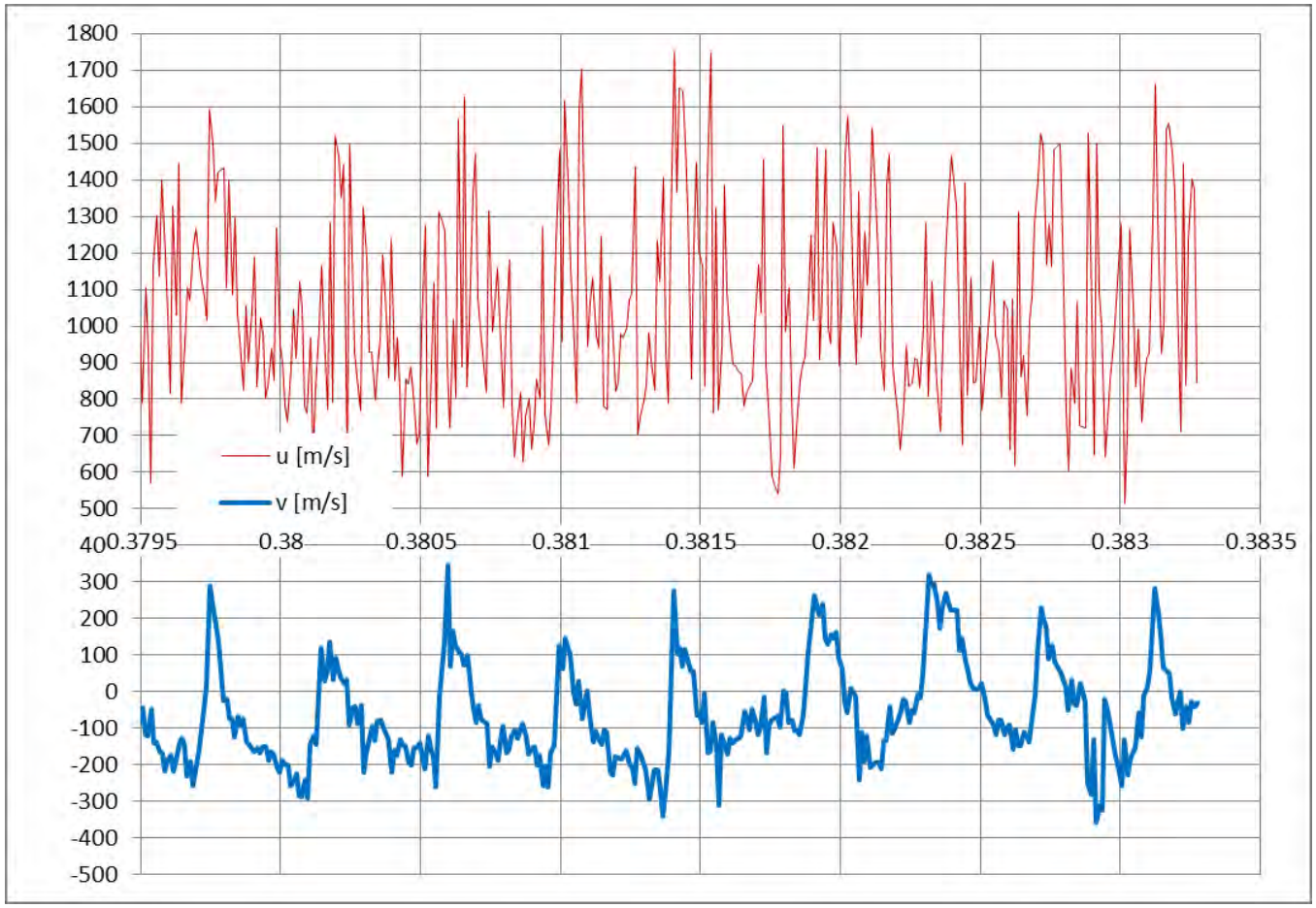

Axial Component

Tangential Component

Wave shape indicates clockwise wave rotation

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Purdue University

Unsteady Turbine Design and Integration

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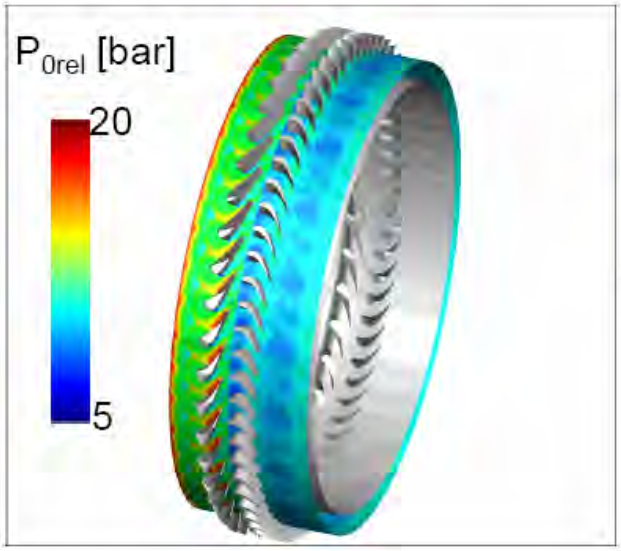
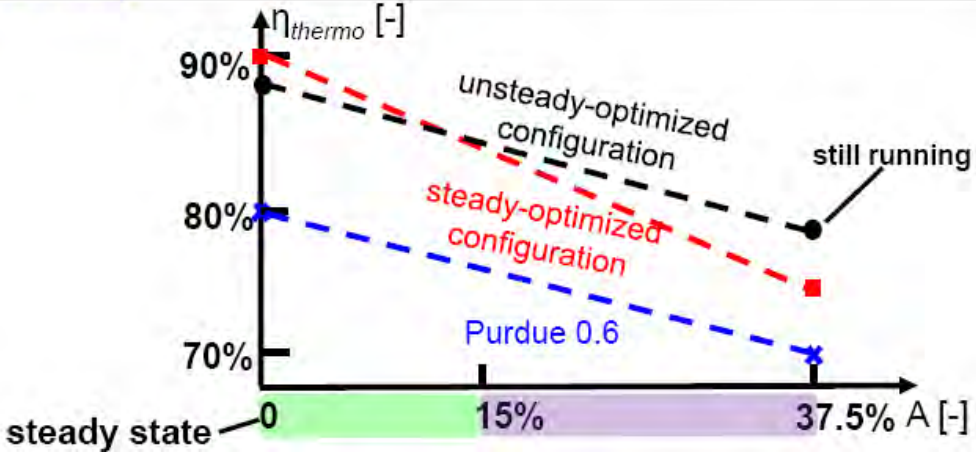
Analysis of optimized turbine stage: exposed to inlet fluctuations

Instantaneous mass flow averaged → *Time averaged of mass flow averaged* → *Turbine efficiency:*

$$\bar{T}_{01}(t) = \frac{\sum_{i=1}^{n} T_{01}(t)\rho_i\left|\overrightarrow{V_{ax\_i}} \cdot \overrightarrow{S_i}\right|}{\sum_{i=1}^{n} \rho_i\left|\overrightarrow{V_{ax\_i}} \cdot \overrightarrow{S_i}\right|} \qquad T_{01} = \frac{\int_0^t m(t)\bar{T}_{01}(t)dt}{\int_0^t m(t)dt} \qquad \eta_{thermo} = \frac{T_{01} - T_{03}}{T_{01} - T_{03s}}$$



	'baseline'	'Purdue 0.6'	steady-optimized configuration	unsteady-optimized configuration
Steady	50%	80%	90%	88%
Full unsteady (f=2kHz, A=37.5%)	-	70.5%	75%	still running



9/13

Engineering Scale RDE Used for Final Demonstration of NETL Program

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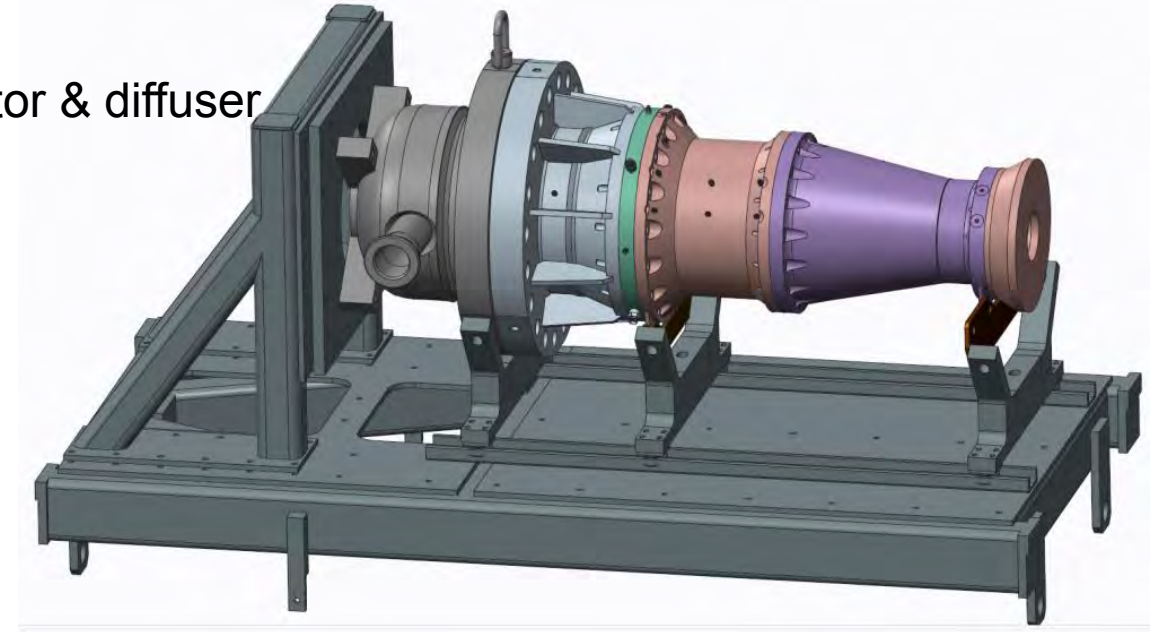
13.4-inch combustion diameter is sufficient to demonstrate air + natural gas without supplemental oxygen

To be tested at Purdue University Zucrow Labs on APEX rig in November 2018

Apply models, tools, & data refined from previous program phases to design injector, chamber and diffuser

Demonstrate operability of injector & diffuser with minimal total pressure loss



13.4-inch Modular Hardware to Allow for Many Injector/Inlet/Exhaust Configurations

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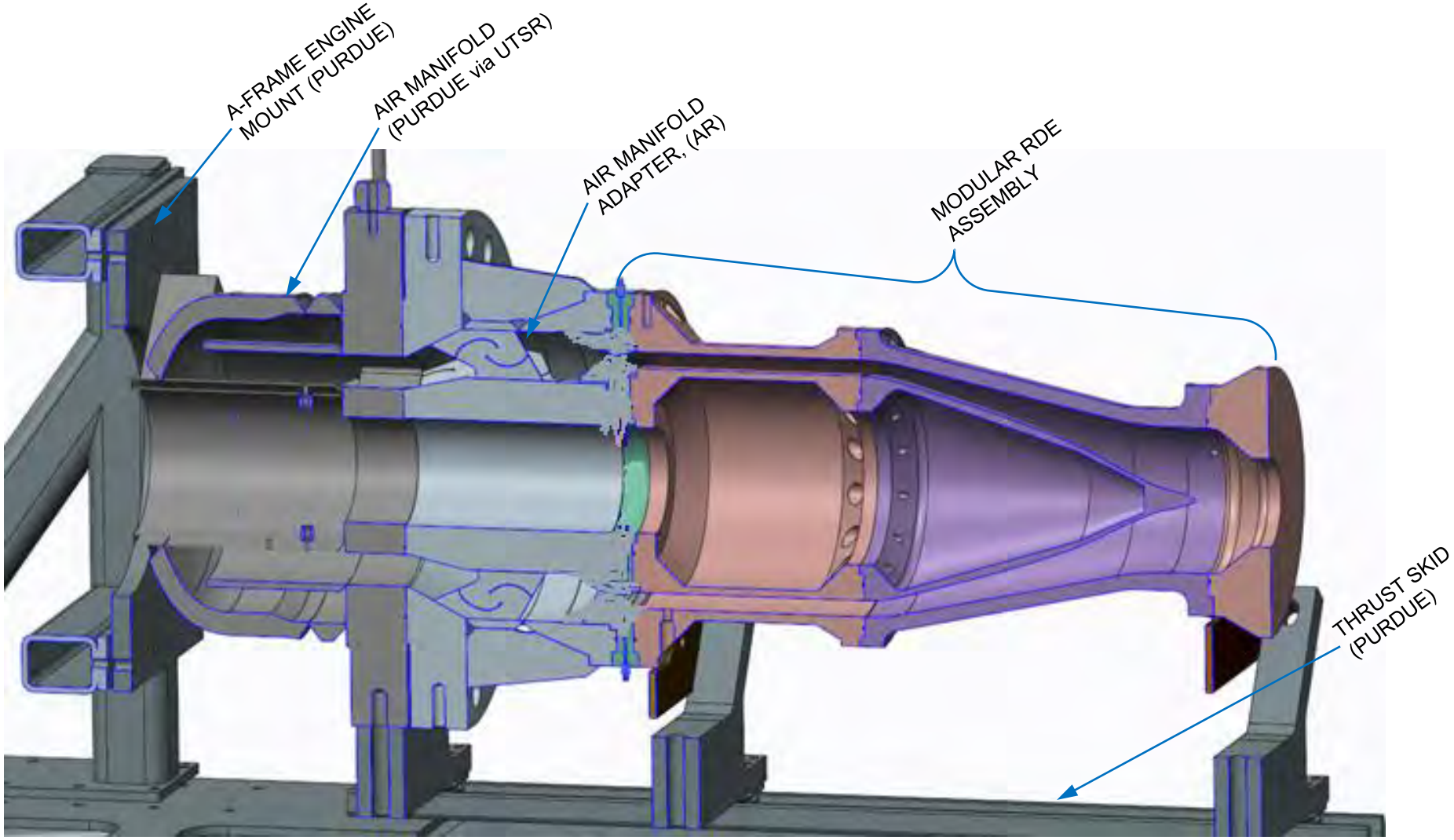

Diffuser Contour Design Tool Improved in 2017, Applied to Engineering Scale RDE

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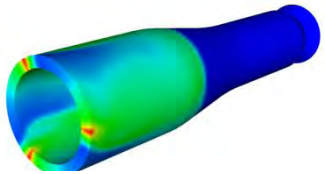
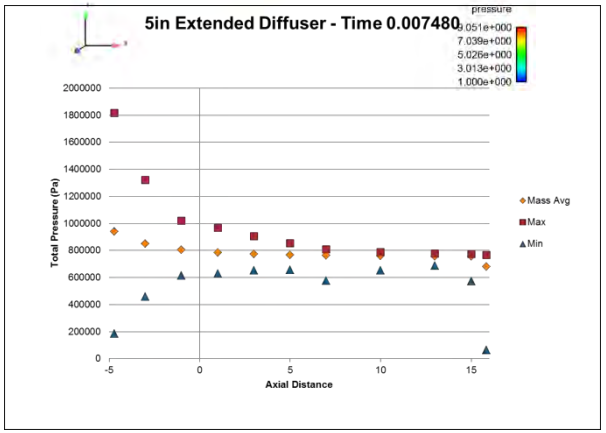


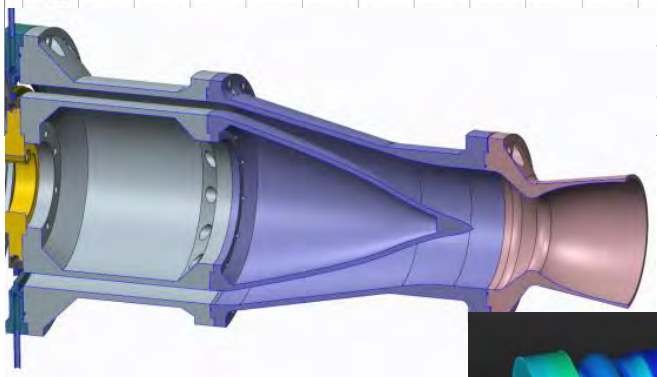
2017 NETL Effort for 4” RDE

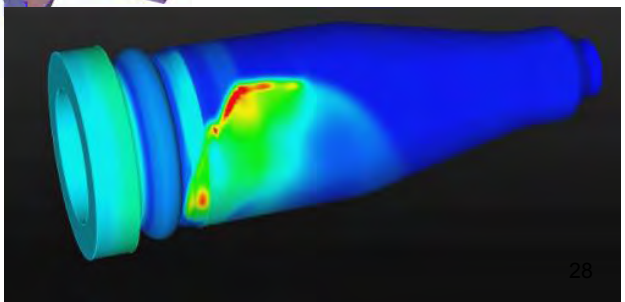


3rd Gen: 20% loss

Diffuser for 13.4” EngrScale RDE

- Convergence angle ~ 12°
- Turning angle radius
- Boundary layer growth allowance
- Additional area growth % rate
- Duct Area Ratio (A_d/A_c) ~ 1.35

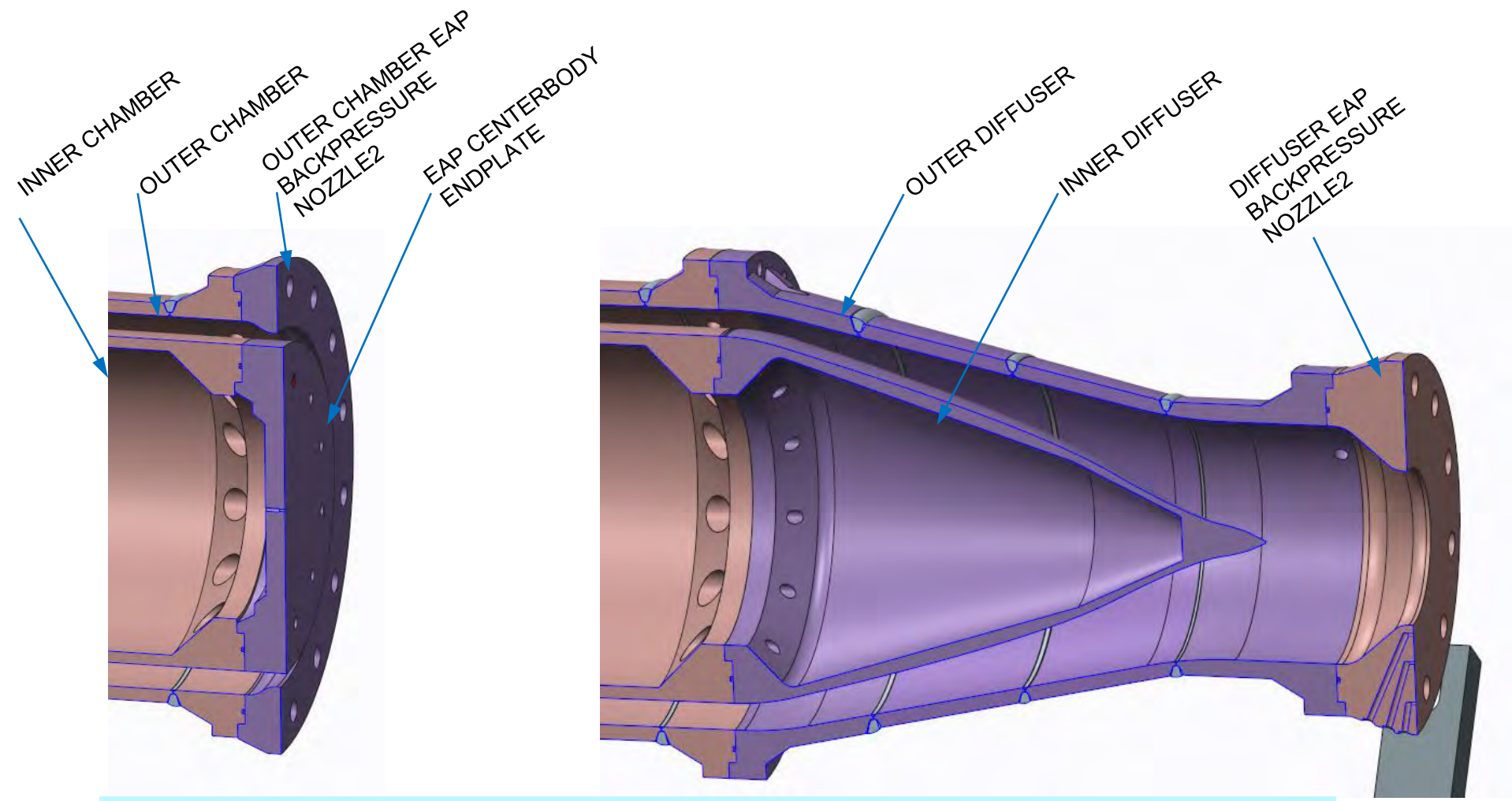




CFD Is Guiding Development of Diffuser Design Tool

Exhaust Options Allow Measurement of Equivalent Available Pressure (EAP) with/without Diffuser

AEROJET ROCKETDYNE



Blunt EAP nozzles with base pressure and thrust measurements allow characterization of detonation combustion and diffuser performance

Hardware Status for October 2018 Test Series

AIR MANIFOLD COMPLETE, INSTALLED

AIR MANIFOLD ADAPTER COMPLETE SHOWN WITH FUEL INJECTORS ASSEMBLED

- Injectors complete.
- All accessory inlets and nozzle rings complete by 15 October.
- Outer combustion chamber completed by 30 October.

Summary and Next Steps

AEROJET ROCKETDYNE

- Under Phase II, a multi-faceted team of researchers is systematically characterizing and optimizing the fluid and mechanical interface between the RDE and a turbine cascade.
  - Multiple test programs have completed and are still underway using 4-inch, 6-inch, 9.4-inch and 13.4-inch RDE combustors with advanced diagnostics.
    - Hot-fire testing is being performed and the University of Alabama, Southwest Research Institute, the University of Michigan and Purdue University (often concurrently).
    - 13.4-inch RDE is being fabricated and will be tested at Purdue in November 2018.
  - CFD models are being developed and anchored as design tools for maximizing RDE and unsteady turbine performance.
  - Empirical and analytical data are providing insight into how to effectively interface an RDE with a gas turbine in a NGCC power plant.