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

DE-FE0023983

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Acknowledgement

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Objective of Program

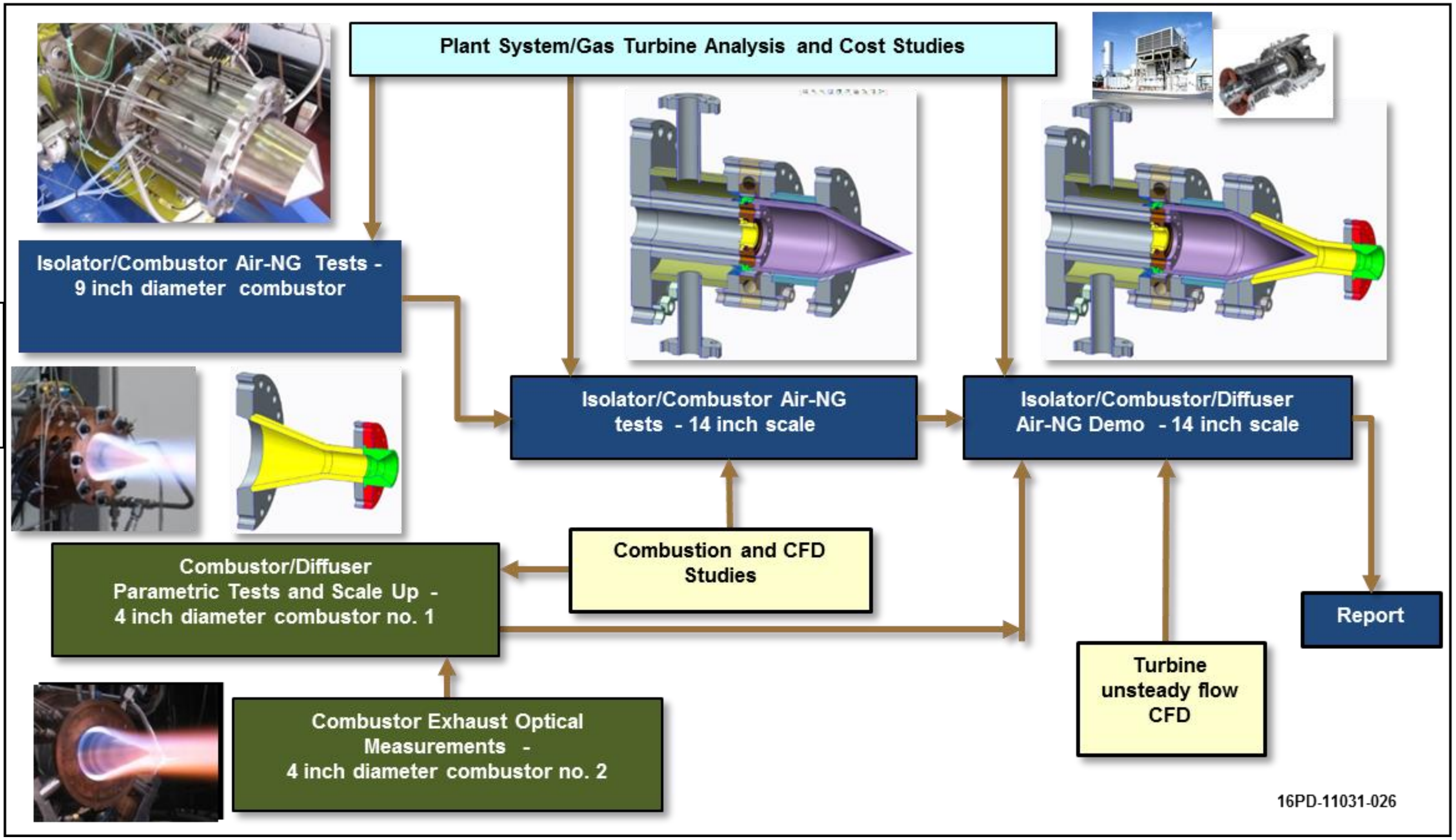
To advance combustion turbine technologies for combined cycle applications…

…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

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**

Phase II Partners

- Aerojet Rocketdyne
  - Project Lead & RDE technology
  - CFD & Model Development
  - Risk Mitigation & Testing Program
  - NGCC Integrated Plant Study
- University of Michigan
  - CFD modeling of RDE for injector & combustion physics
  - Investigate injector and combustion dynamics
  - Test diagnostics
- University of Alabama
  - Test facility with 10 cm RDE2 and various diffuser geometries.
  - Optical diagnostics for combustor and diffuser exhaust flow characterization.
  - Test Operations
- Purdue University
  - Flow Effects on Turbine Efficiency
  - Turbine Blade Unsteady Flow Analysis
  - NG/Air test facility with 9.4 inch RDE
  - NG/Air test facility with 14 in RDE
  - Test Operations
- Southwest Research Institute
  - Test facility with 10 cm RDE1 and various diffuser geometries
  - Test Operations
- University of Central Florida
  - High fidelity optics diagnostic for composition and unsteady flow analysis
- Duke Energy
  - NGCC integrated plant study support and review
  - Funding Partner

Approved for Public Release

Project Task Summaries

- **Task 1 Program Support (Aerojet Rocketdyne)**
  - Provide overall program management for the RDE4GT project to facilitate coordination and management of technical efforts, subcontracts and suppliers, schedule and budget.
- **Task 9 System Engineering and Analysis (Aerojet Rocketdyne, Purdue)**
  - Define RDE requirements and lead system analysis technical execution and project coordination.
  - Lead studies on turbine blade interaction with unsteady flows, and update Natural Gas Combined Cycle (NGCC) power plant study.
- **Task 10 CFD and Model Development (Michigan, Aerojet Rocketdyne)**
  - Upgrade and validation of AR CFD models (URANS and LES) for RDE performance
  - UM conducts Large Eddy Simulation (LES) CFD analysis of AR RDE to quantify PGC and calibrate AR CFD kinetic models
  - UM tests AR injector designs with diagnostic tools visualizing unsteady flow physics
- **Task 11 Unsteady Measurements (Alabama)**
  - UA will conduct tests with RDE combustor and diffuser configurations to obtain exiting flow field data to determine hardware pressure losses. CFD predictions will be reviewed and the codes updated.

Project Task Summaries

- **Task 12 Isolator/Combustor Risk Reduction (Purdue)**
  - Purdue will test the updated designs of the 9.4 inch RDE with NG/Air and the test data compared to CFD/model predictions, status component efficiencies and to update the analytical models
  - Based on the task 11 and 12 test data and analysis, AR will design the Engineering Scale RDE Combustor.
- **Task 13 Diffuser Risk Reduction (Southwest Research Institute)**
  - SwRI will test diffuser concepts coupled with a 4 inch RDE provided by AR. Test data will be compared to CFD/model predictions, status component efficiencies and to update the analytical models.
  - Based on the diffuser test data and analysis, AR will design the Engineering Scale RDE Diffuser
- **Task 14 Engineering Scale Integrated Testing (Purdue)**
  - Purdue will test the integrated Engineering Scale RDE and provide optical diagnostics to verify PGC in the larger scale RDE.
- **Task 15 RDE Test Diagnostics (University of Central Florida)**
  - UCF will research, develop, and procure advanced optical diagnostic instrumentation to analyze RDE exhaust flows. Data acquired will determine mass flux averaged total gas pressures, gas velocities and combustion species.

Task 9.3 Summary: Characterize Flow Effects on Turbine Efficiency

- **Develop operating conditions of a commercial-scale RDE that defines the exhaust flow into a commercial power generating gas turbine.**
- **Analyze turbine/compressor sensitivities to RDE unsteady flow generation.**

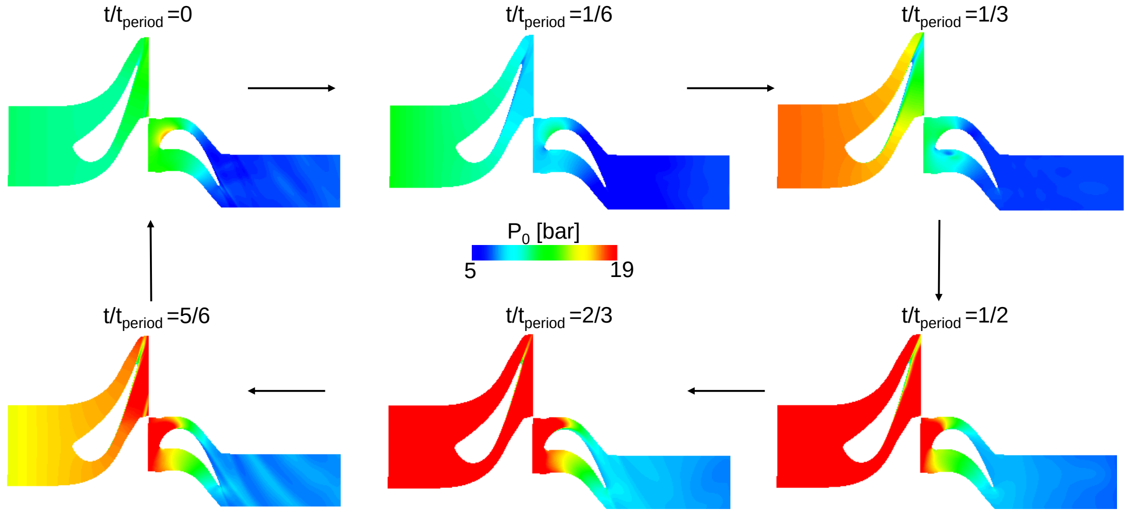
Task Goals:

- **Find commercial gas turbine unsteady operating regime where 1st stage unsteady isentropic efficiency will be greater than 88%.**
- **Develop 1st stage performance model for unsteady flow in a commercial turbine.**
  - **With average stagnation turbine inlet conditions: 240 psia & 2,780F**

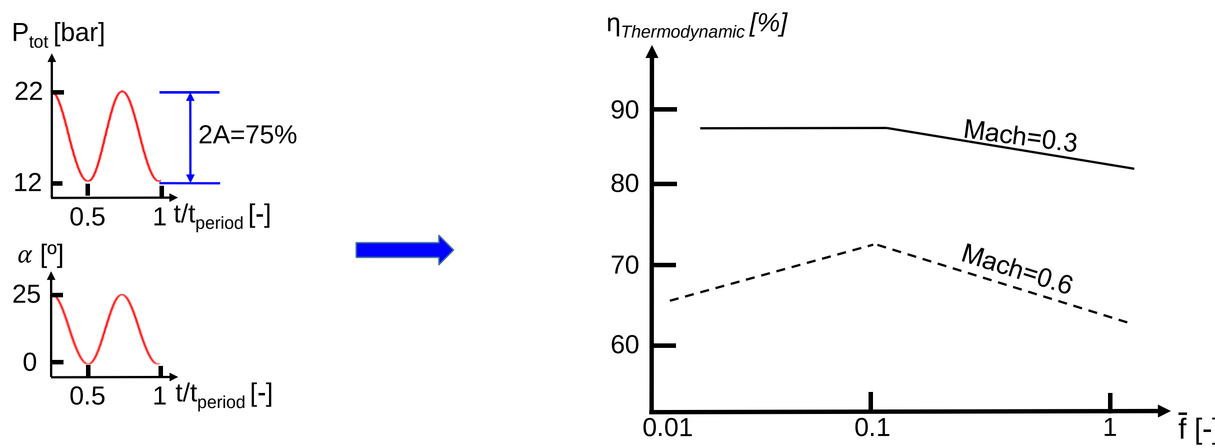
Task 9 – Systems Analysis
Purdue University and Aerojet Rocketdyne

- **Dr. Guillermo Paniagua (unsteady turbines) and Ken Sprouse (system engineering) are task leaders**

- **Completed preliminary assessment of unsteady turbine performance using RANS and URANS simulations with oscillating pressure and flow angle**

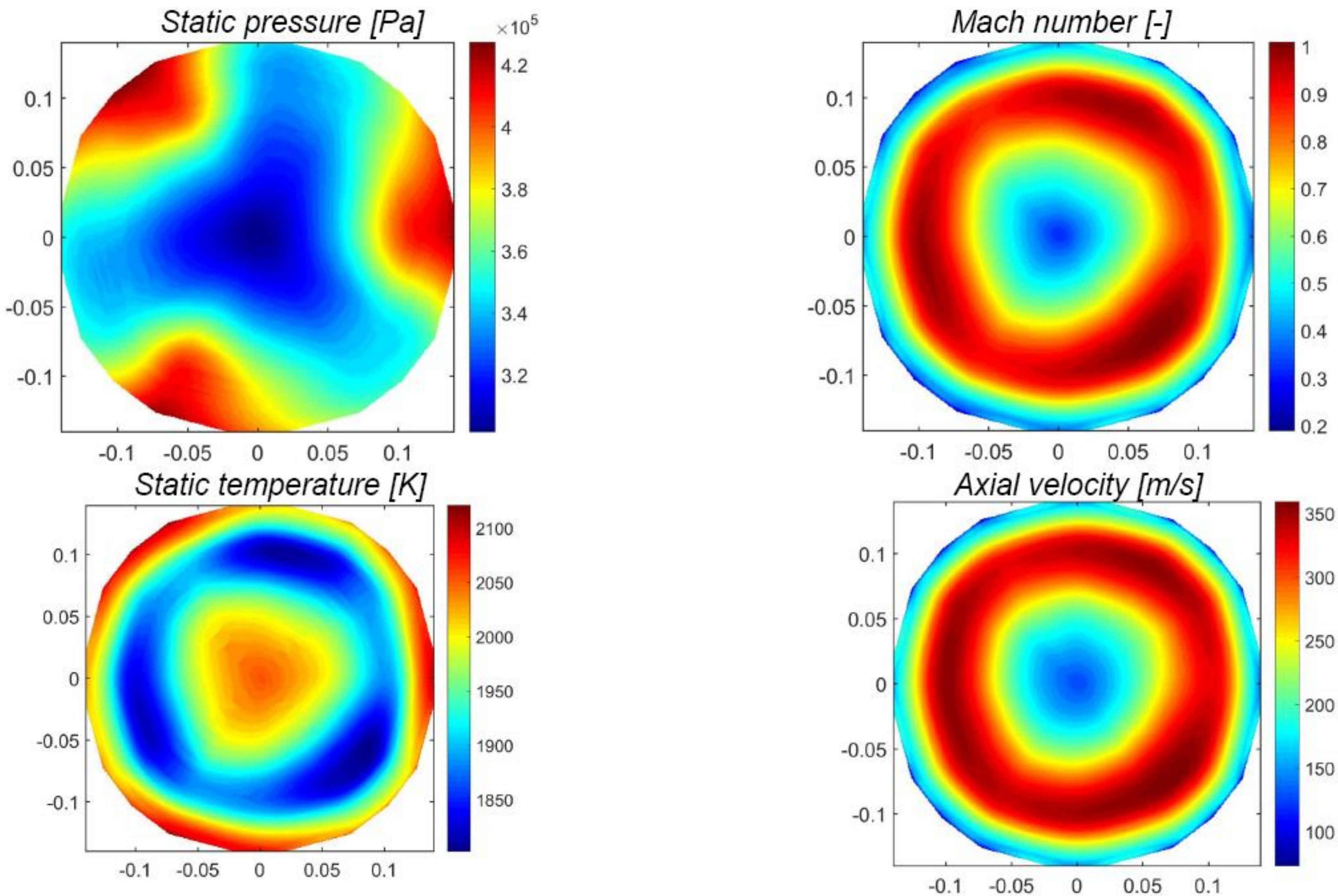


One periodic cycle of an URANS stage simulation (Mach=0.3, f=1 kHz, and A=37.5%)



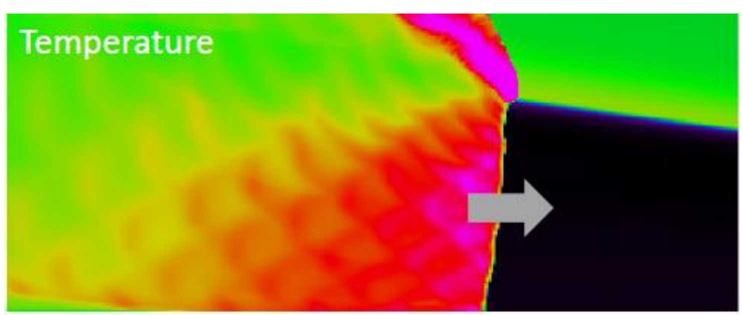
Subtask 9.3 -- RDE Diffuser Exit (Stream 10)

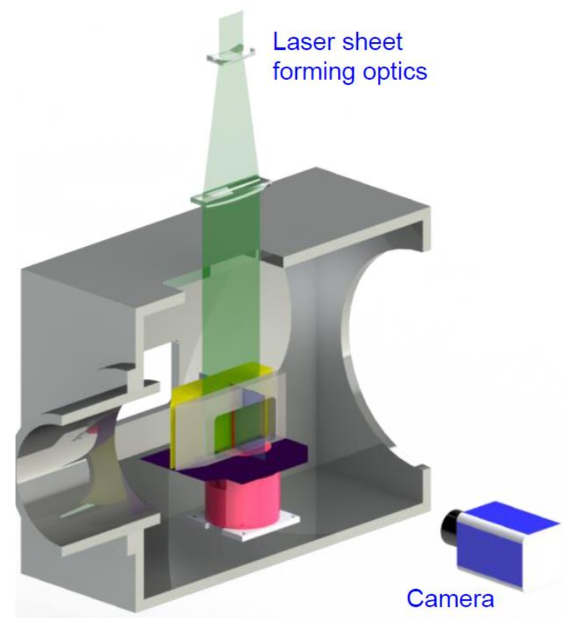
Unsteady High-Speed High-Amplitude Periodic Flow



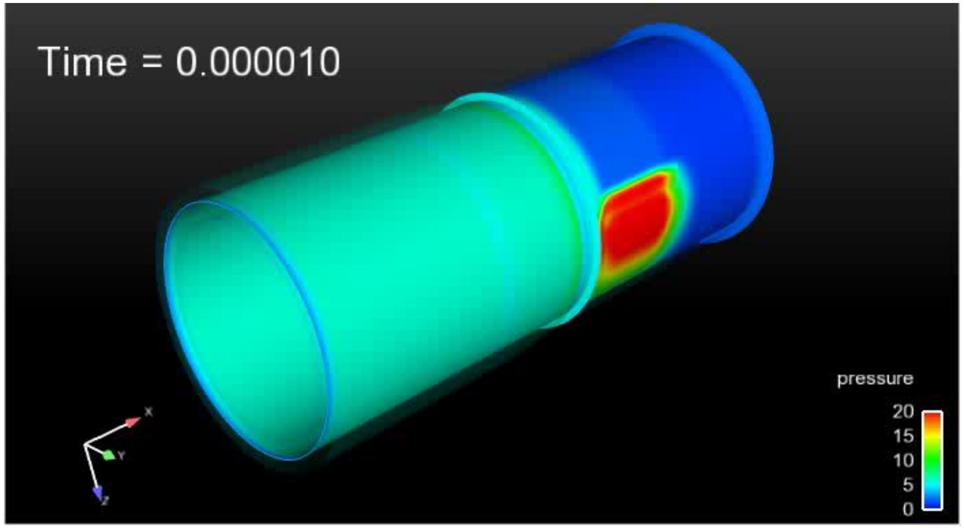
Task 10 – CFD and Model Development, University of Michigan

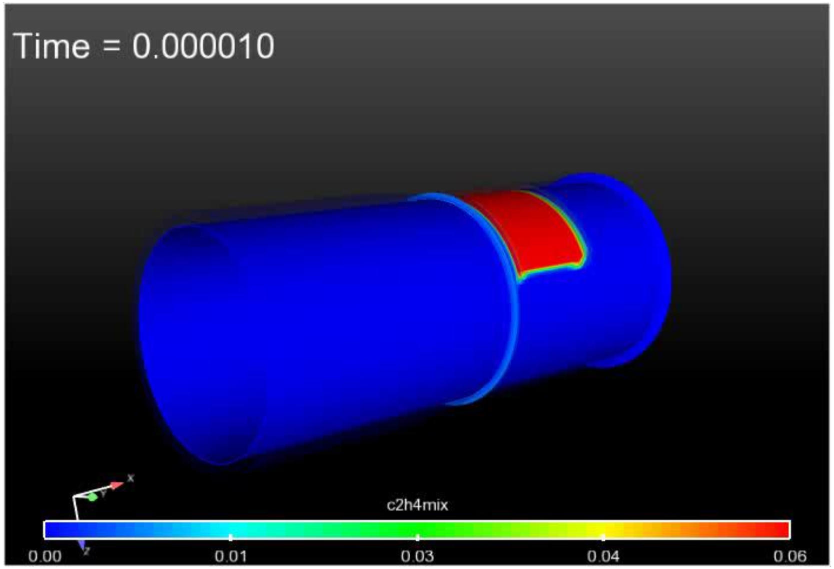
- Dr. Mirko Gamba (Subscale Testing) and Dr. Venkat Raman (RDE CFD) are task leaders
- Leverage developments on Michigan's current UTSR contract
- Use visualization diagnostics on a realistic injector configuration
- Use anchored CFD code to quantify losses, including non-equilibrium effects on detonation
- Extend tools from other RDE programs to understand results from test and upgrade performance modeling





Task 10.1 Performance and CFD Tools: URANS Modeling with Various Fuels/Geometries



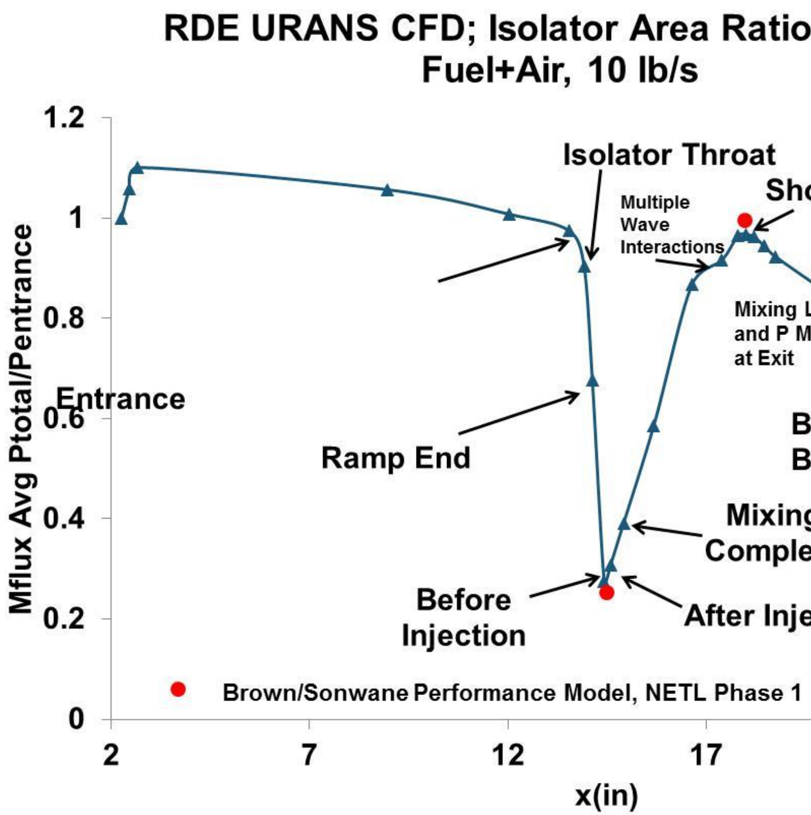


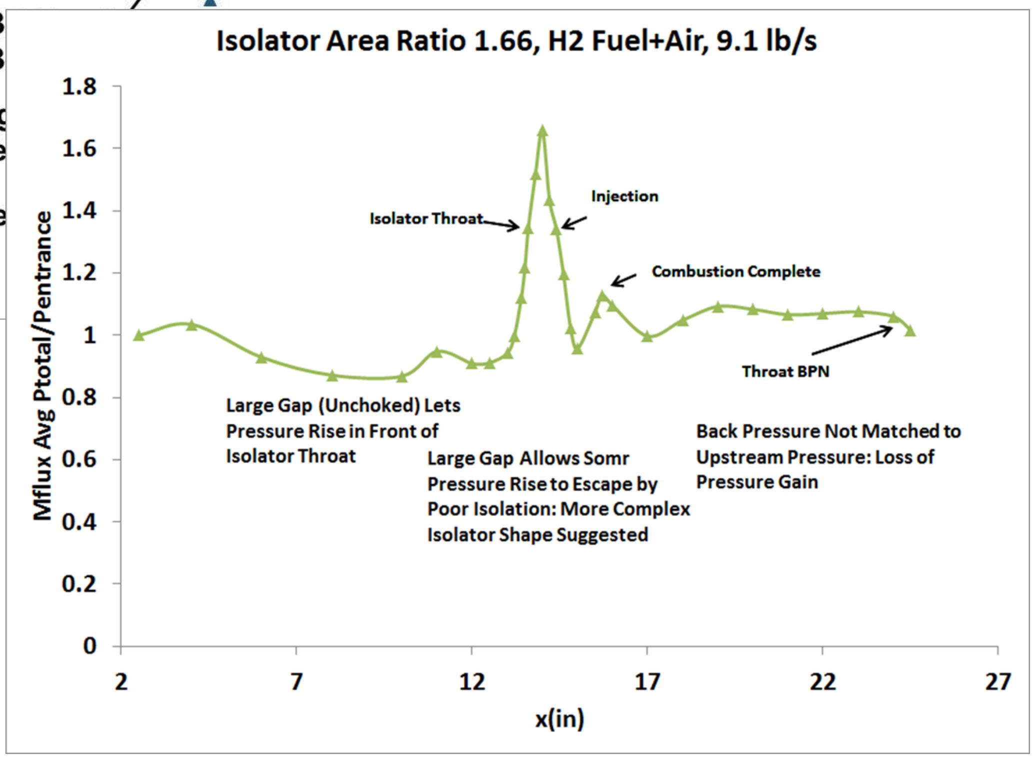
Quasiglobal Kinetics with Special Treatment of Source Term to Capture Detonation Waves

Velocity and Pressure inline with CJ values

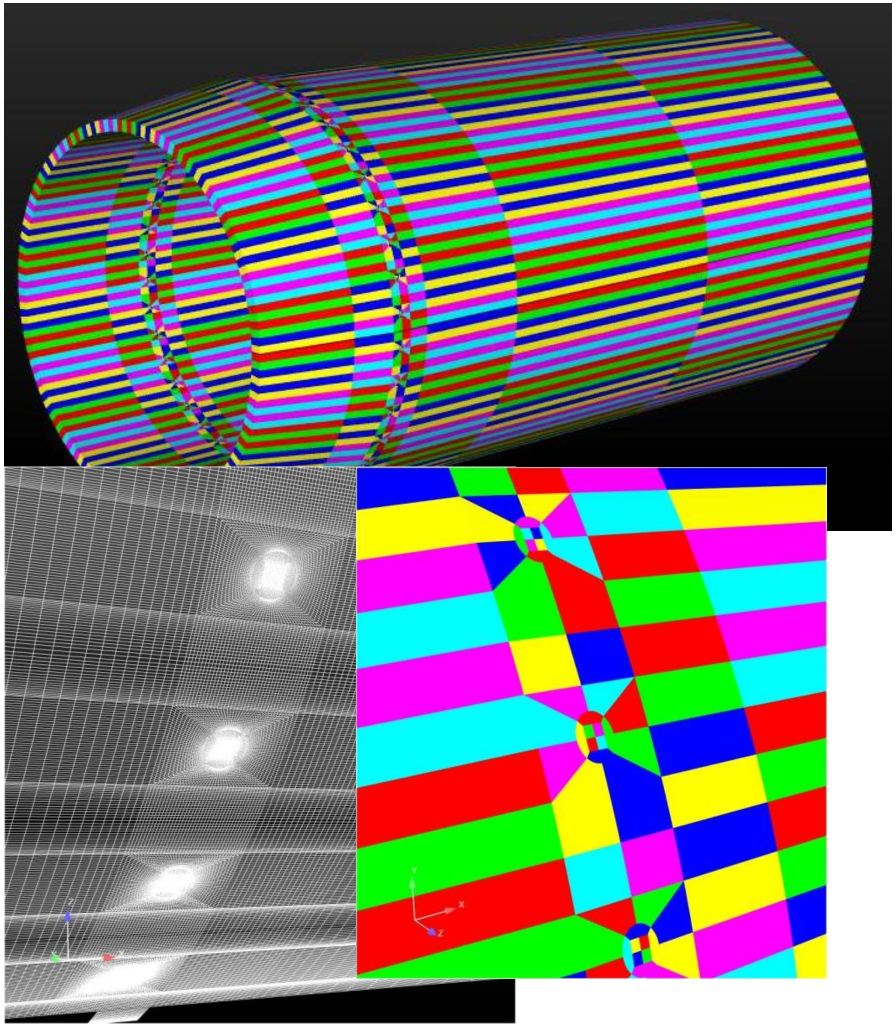
Self-Similar Solution for C_2H_4 4:1 Area Ratio with Baseline1-D Mixing Rate

Task 10.1 Performance and CFD Tools: Isolator Area Reduction Enables Pressure Gain

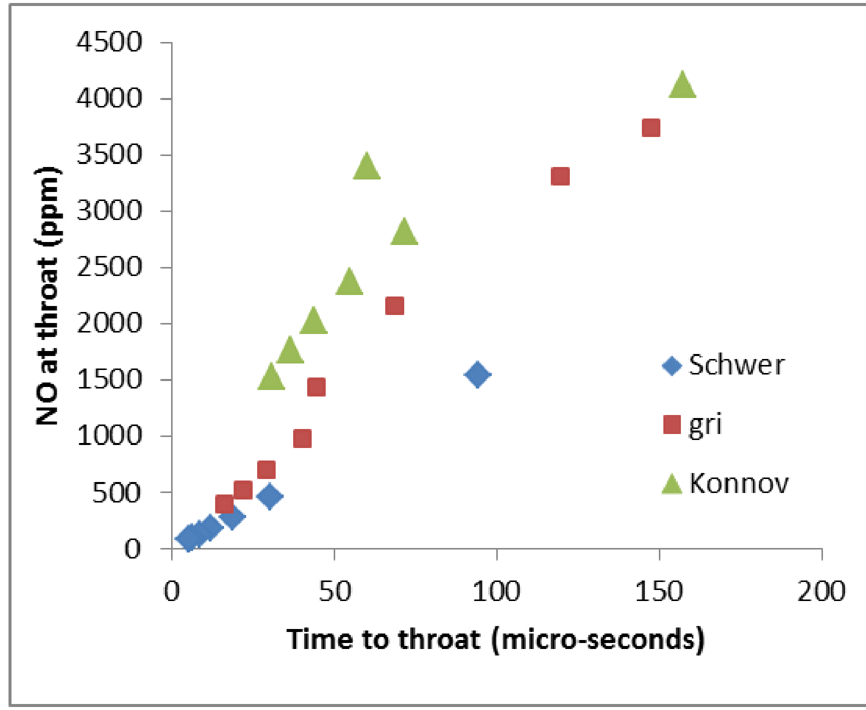




Task 10.1 Performance and CFD Tools: NOX and LES Modeling



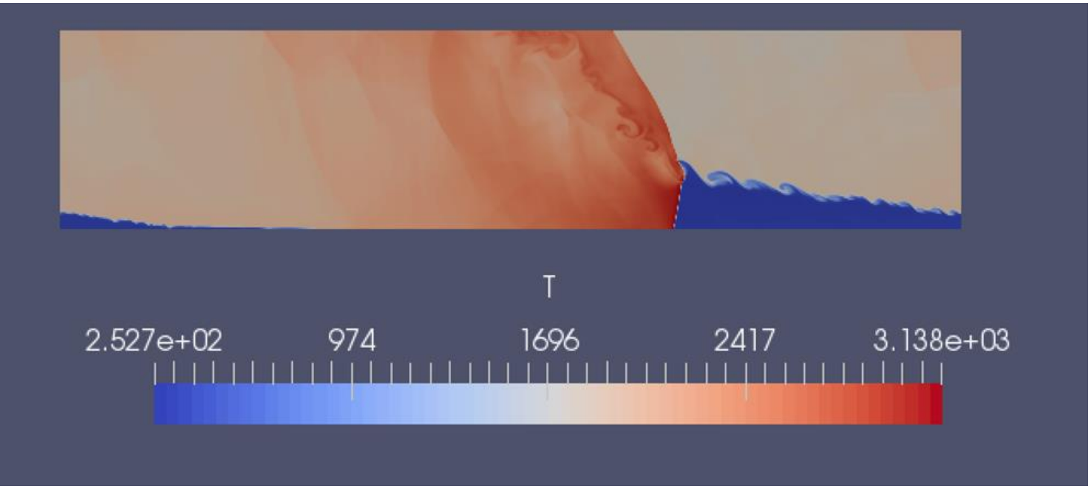
Grid for 3-D AHFM LES Modeling



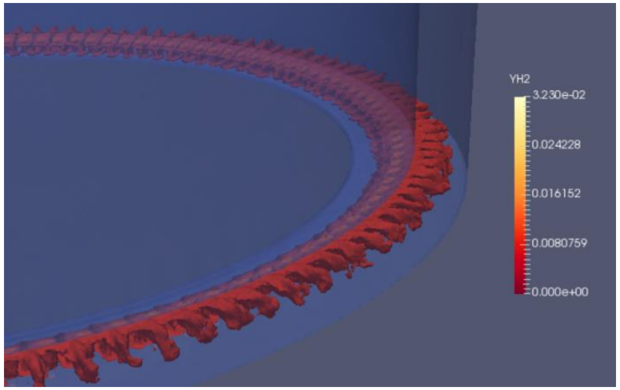
- Faster Mixing Reduces NOX
- Detailed Kinetics Increases NOX

Task 10.2 – University of Michigan

CFD Modeling Provides Platform to Update Mixing & Kinetics



- UM Unrolled RDE with Detailed H2 Kinetics
- Parametrics Underway: Variable Area Ratio for Pintle Geometry Similar to AR Concepts

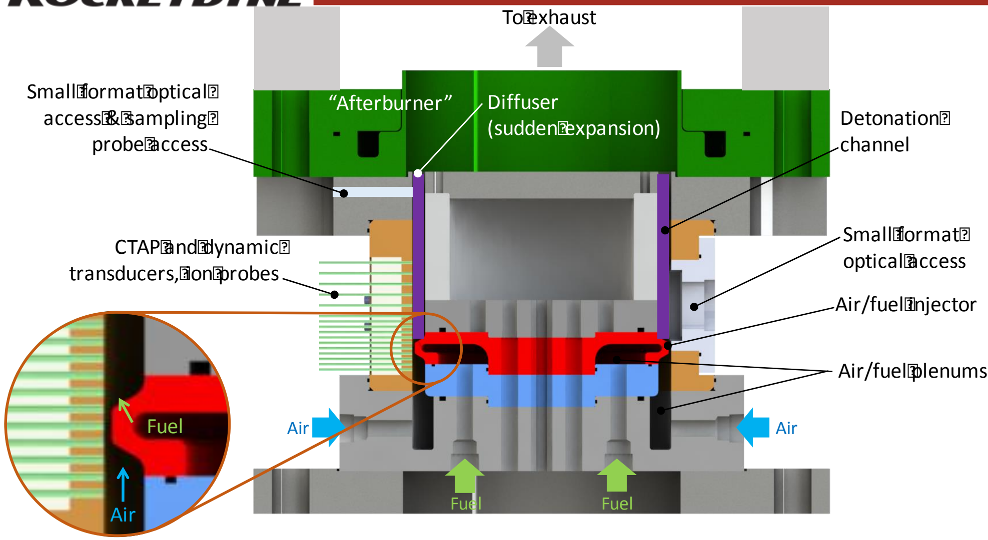


Multiple Injector LES CFD

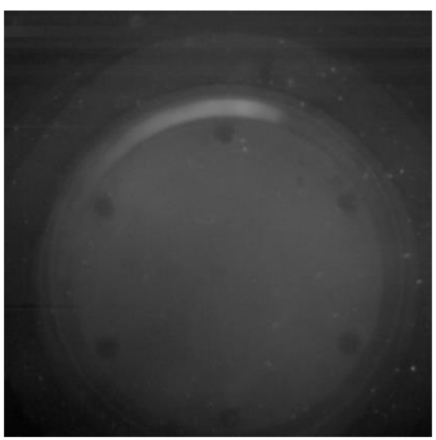
- Finite Volume Method (FVM) used for CFD modeling with
  - OpenFOAM framework
  - Adaptive Mesh Refinement (AMR)
  - Single step chemistry initially used
    - Updated to multi-step
- Hydrogen/air reactant systems
- Full scale injector simulations being implemented
  - Better understanding of jet penetration and mixing process with dependency on chemistry and shock front
- Final detailed CFD to be correlated Against 6" RDE hot fire tests (Task 10.3)

Task 10.3 – University of Michigan

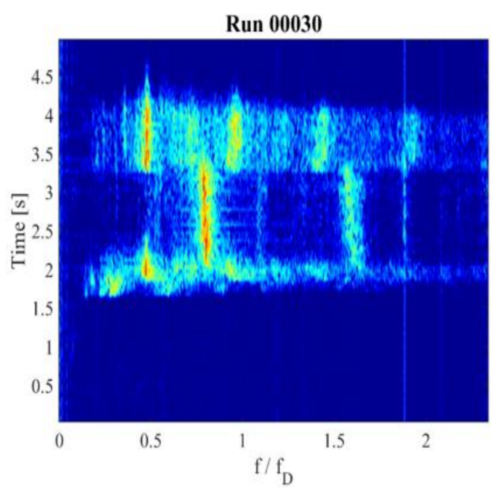
Hot-Fire Testing Provides Data For CFD Model Correlation



6" Dia Round Quartz Chamber RDE Layout



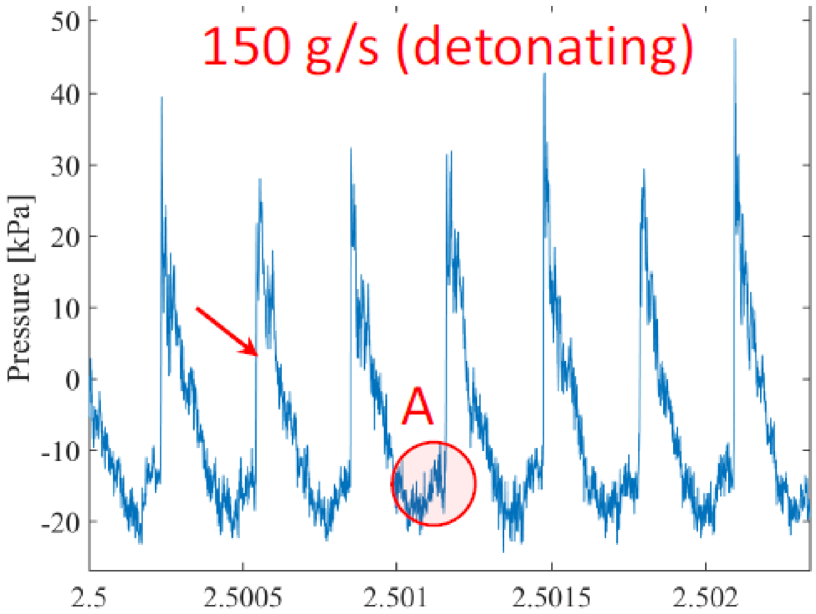
Chemiluminescence Image

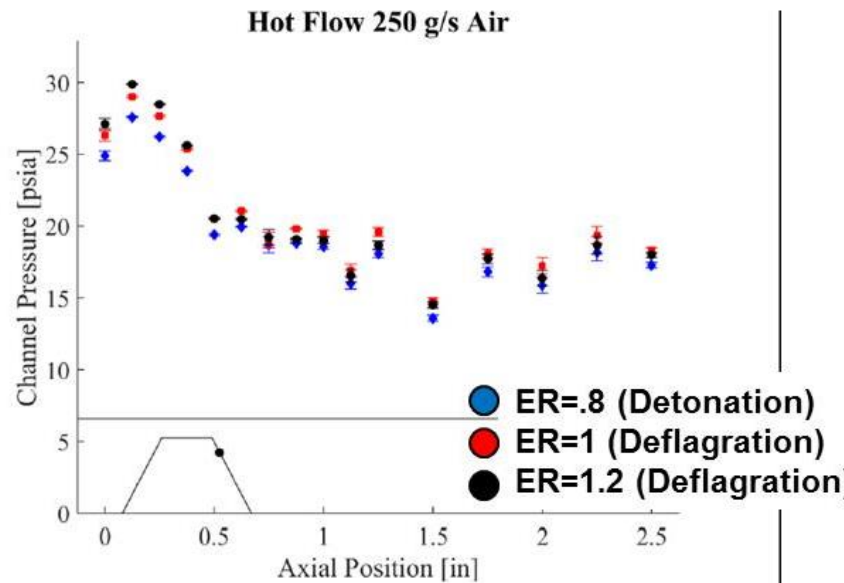


External Acoustics Waterfall Spectrum Plot

- **Initial testing of a 6" diameter round quartz chamber RDE**
  - **Incorporates half of an AR style injector/isolator to accommodate the quartz chamber**
  - **Hydrogen/air reactant system**
- **High speed data collected to date**
  - **End view chemiluminescence images showing rotating detonations**
  - **External acoustic (microphone) measurements showing strong response at 80% of CJ frequency, f_D**
- **Expect changing RDE to a 12" oval racetrack quartz chamber**
  - **Adds better flow visualization with laser diagnostics through chamber side wall**

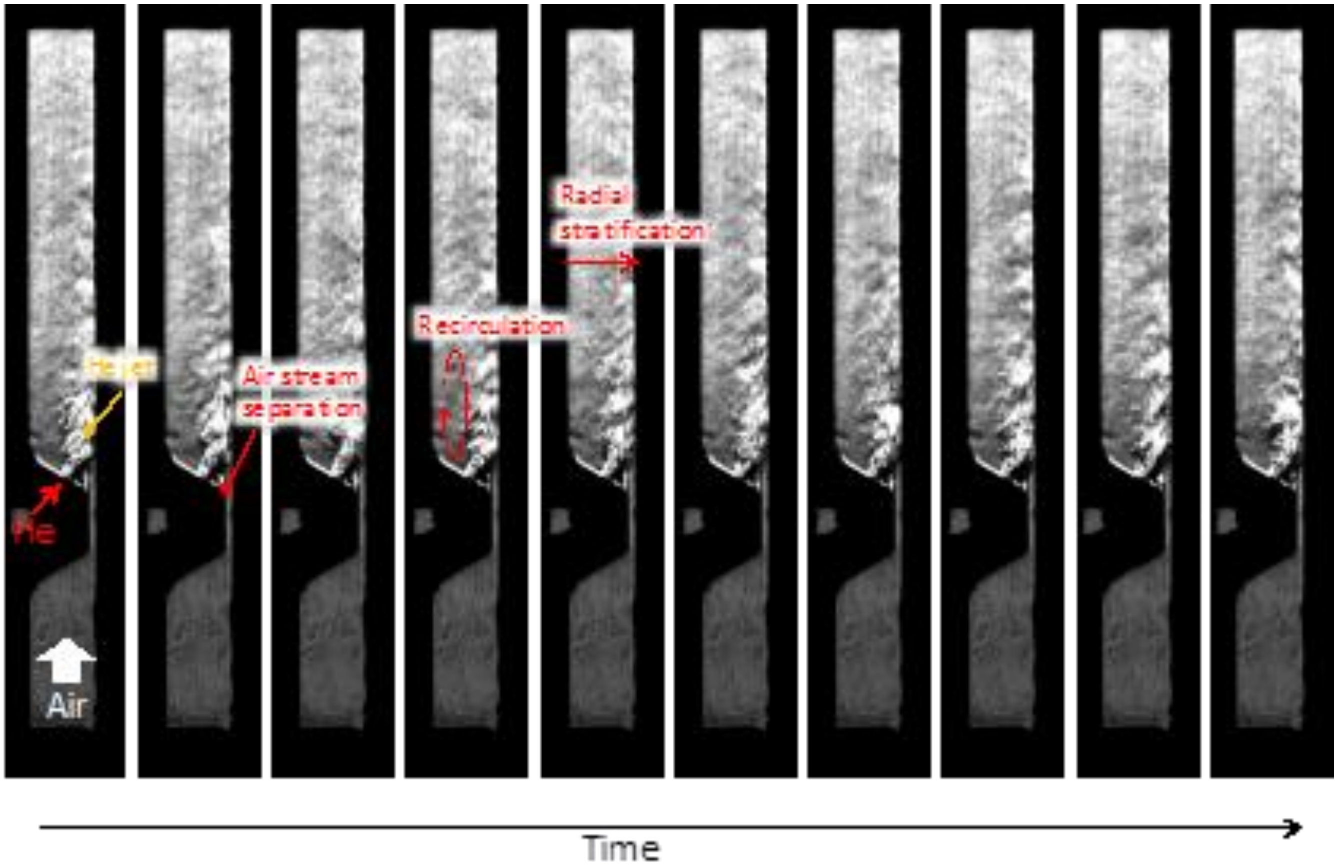
Task 10.3 – University of Michigan
Hot-Fire Testing Provides Data For CFD Model Correlation





- **Pintle Injector Detonation: Similar to AR System**
- **Lower Manifold Pressure with Detonation for Fixed Back Pressure Indicative of Pressure Gain**

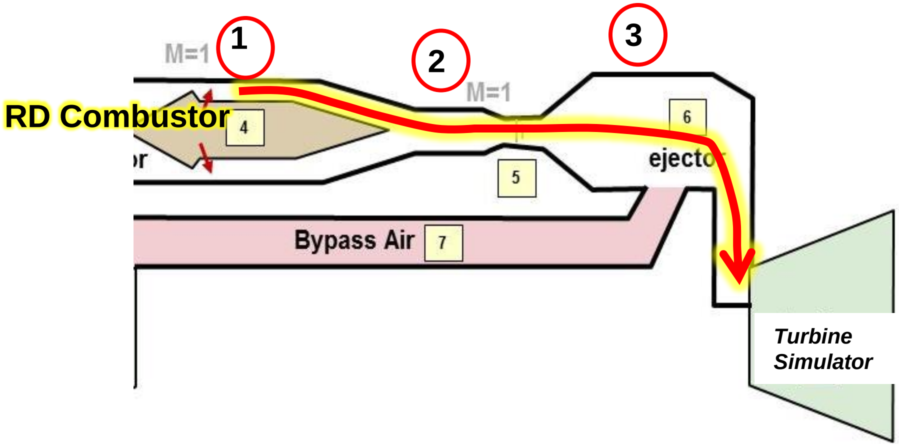
UM Schlieren Visualization of Fuel Injection Illustrates Key Role of Mixing in Attaining Performance Gain

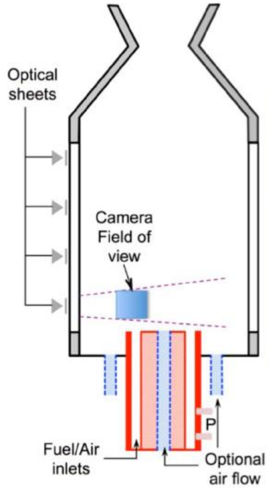


Stratified Flow from Rapid Expansion Leads to Recirculation Region and Poor Mixing, Potential for Instabilities

Task 11 – Unsteady Measurements, University of Alabama

- **Dr. Ajay Agrawal is task leader**
- **PIV, Chemiluminescence and PLIF at 20 KHz to characterize unsteady flow at the exit of the RDE.**
- **Set up existing AR 10 cm RDE at UA and operate on enriched air and methane**
- **Test AR 10cm RDE with representative diffuser and mixer geometries**





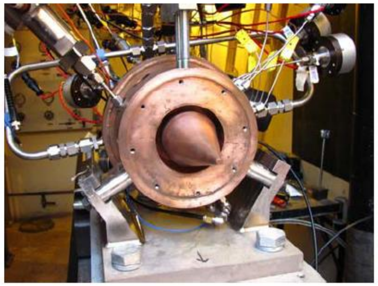
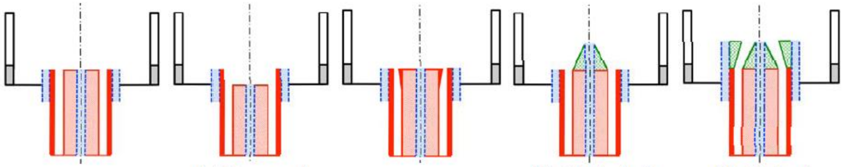


Fig. 3: (a) Schematic diagram illustrating RDE integrated with the mixing chamber, (b) photograph of the high-pressure combustion test rig to be modified for the proposed study, and (c) Example of RDE hardware at Aerojet Rocketdyne that will be utilized in this study.



(a) Flush aftend | (b) Recessed aftend | (c) Plug nozzle | (d) Unchoked aerospke nozzle | (e) Choked aerospike nozzle

Task 11 – Unsteady Measurements, University of Alabama

Task 11.1 Summary: Optical Combustor Exhaust Flow Characterization

- Prepare text matrix and instrumentation diagnostics requirements
- Modify UA test facility and install AR 4” diameter RDE
- Conduct testing and perform pressure gain analyses

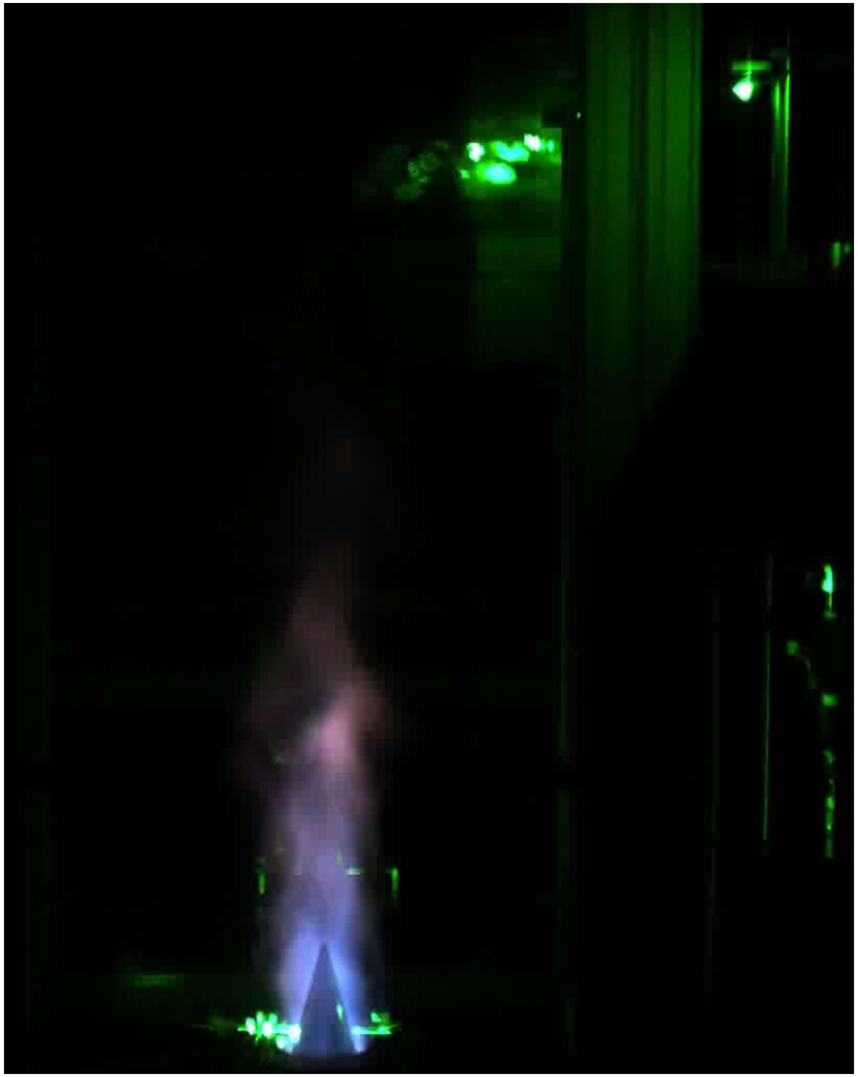
Task Goals:

- Obtain PIV and Chemiluminescence optical diagnostic measurements that are reproducible and quantitative for use in subsequent RDE performance analyses.
- Show that average stagnation pressure gain across RDE combustion chamber is greater than 2.0.

Task Status:

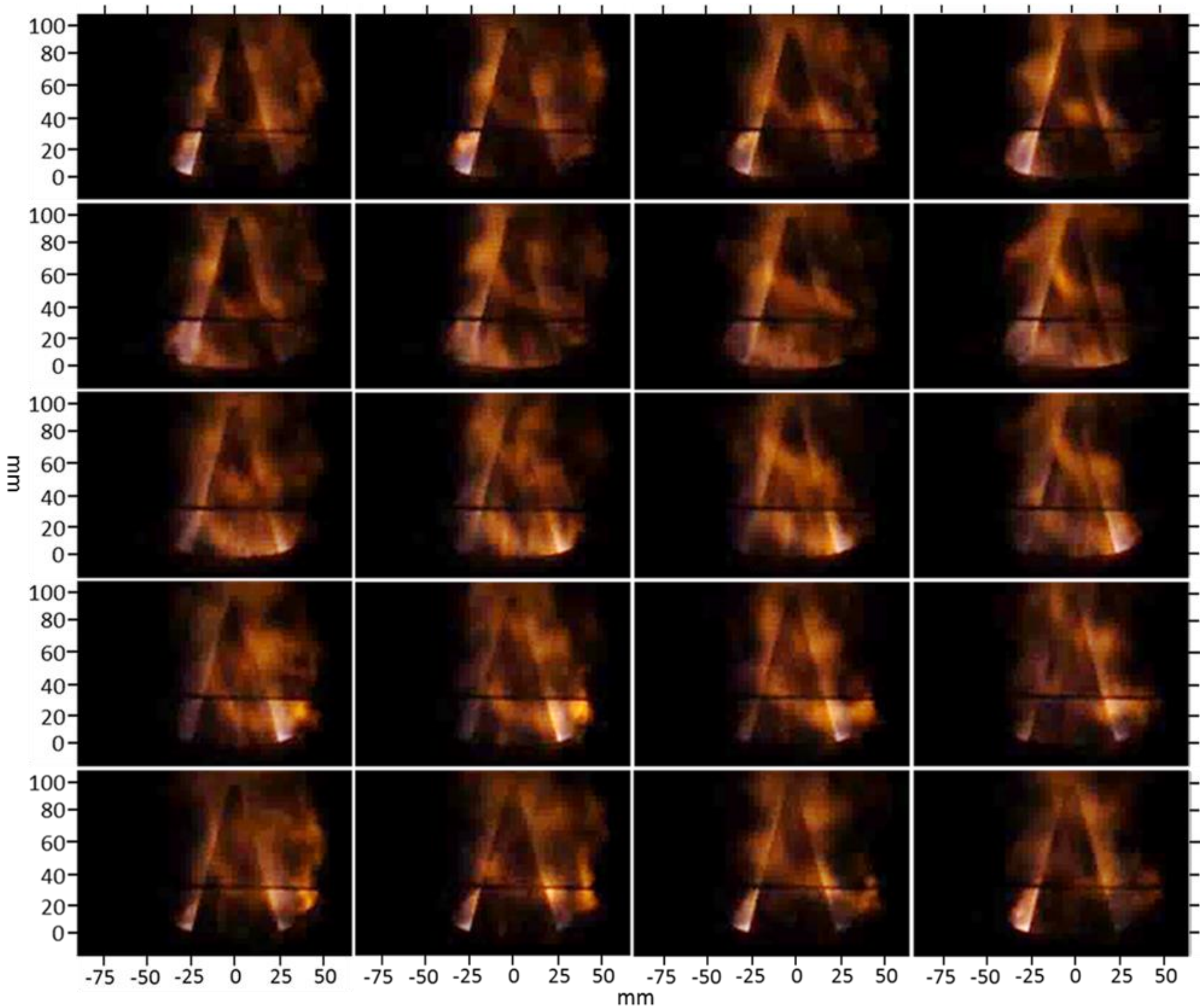
- RDE is operating effectively with methane and enriched air.
- PIV system has been activated using ZrO_2 seeding.
- Combustor unsteady flow field testing on-going.

Subtask 11.1 -- UA High Speed Video Pics



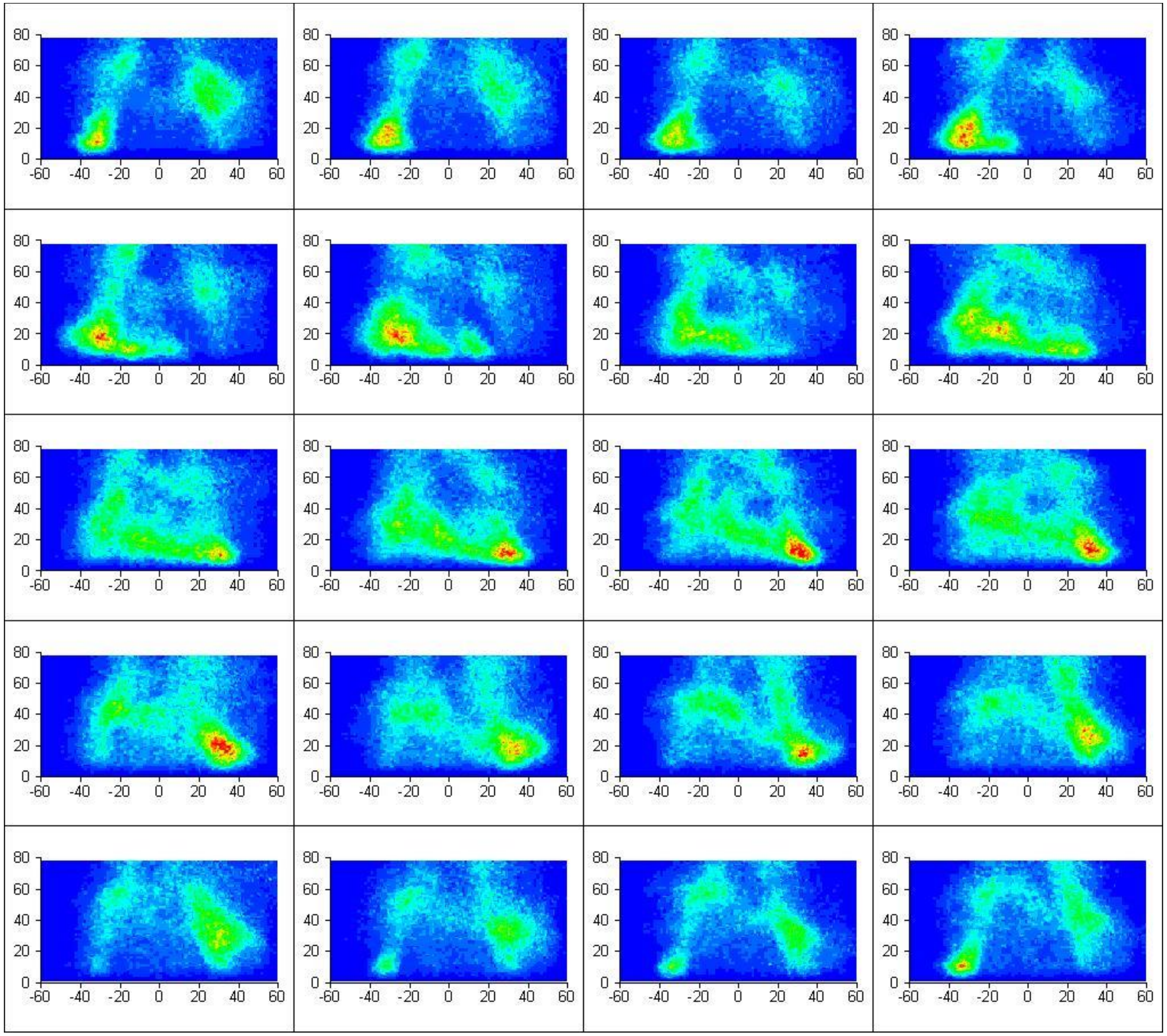
Subtask 11.1 – Improved UA High Speed Video Pics

- **At 30 kHz Framing Rate - showing angular wave speed, $s_{\theta,w}$, at ~ 6,283 ft/sec**



Subtask 11.1 – Chemiluminescence at 30 kHz

- **At 30 kHz Framing Rate -- showing angular wave speed, $s_{\theta,w}$, at ~ 6,283 ft/sec**

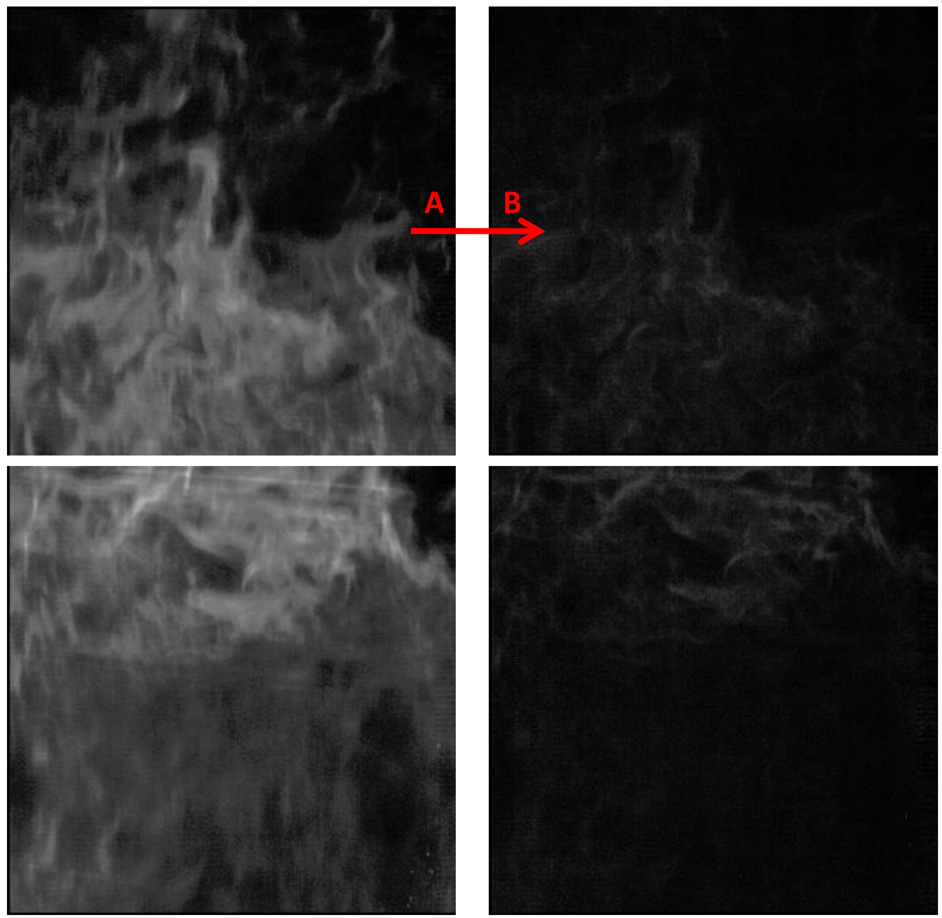


Subtask 11.1 – Initial PIV at 37 kHz

- Time interval between Frames 29A and 30A is approximately 27 micro-seconds
- Time interval between Doublet A and B is approximately 1 micro-second
- Light pluse illumination duration is 0.1 microsecond
- Average illumination energy is 12 mJ

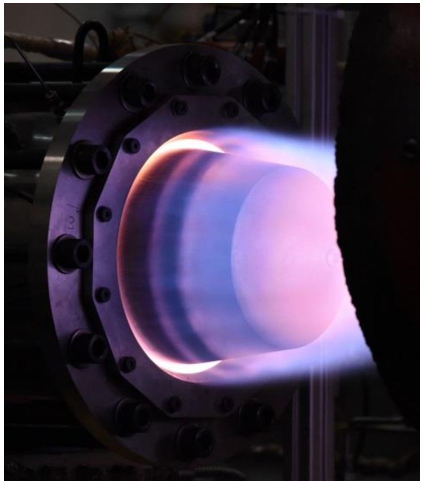
29

30

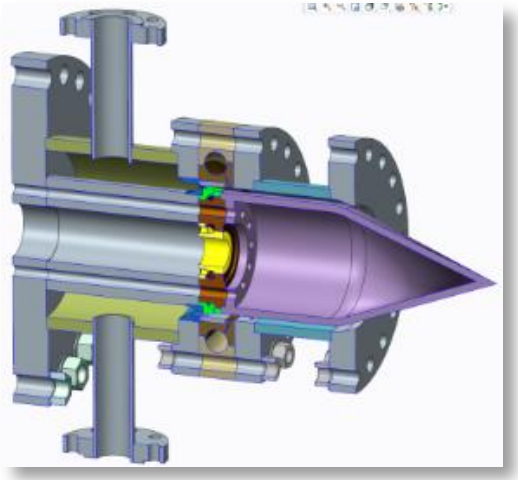


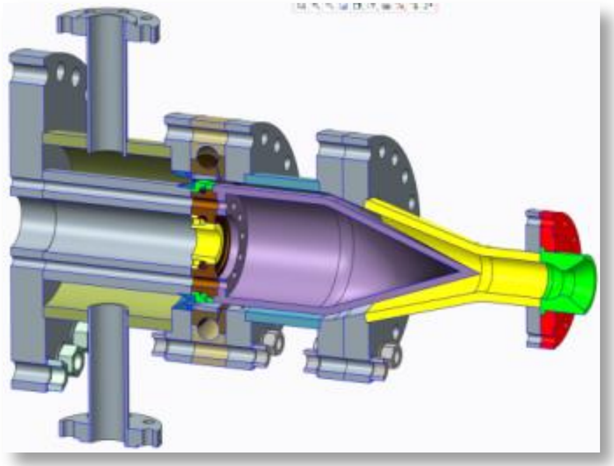
Task 12 Isolator/Combustor Risk Reduction
Purdue University

- **Dr. Carson Slabaugh (RDE testing) is task leader**
- **Leverage developments on Purdue's current UTSR contract**
- **Hot-fire test the existing 9.4-inch RDE with air/natural gas to assess injector/isolator effectiveness.**
- **Design a large-scale integrated Inlet/Combustor/Diffuser for testing at 40 lbs/sec of air flow.**



9.4-inch RDE has been delivered to Purdue. First test in November 2017





Conceptual design of the large scale RDE is underway

Task 12 Isolator/Combustor Risk Reduction, Purdue University

Task 12.1 Summary: Air Breathing 9.4 inch Isolator/Combustor

- Prepare text matrix and instrumentation diagnostics requirements
- Build-up new APEX test cell at Purdue's Zucrow facility
- Install AR 9.4" diameter RDE
- Conduct testing on two AR Injector/Isolator designs and perform pressure gain analyses using equations presented in Subtask 11.1.

Task Goals:

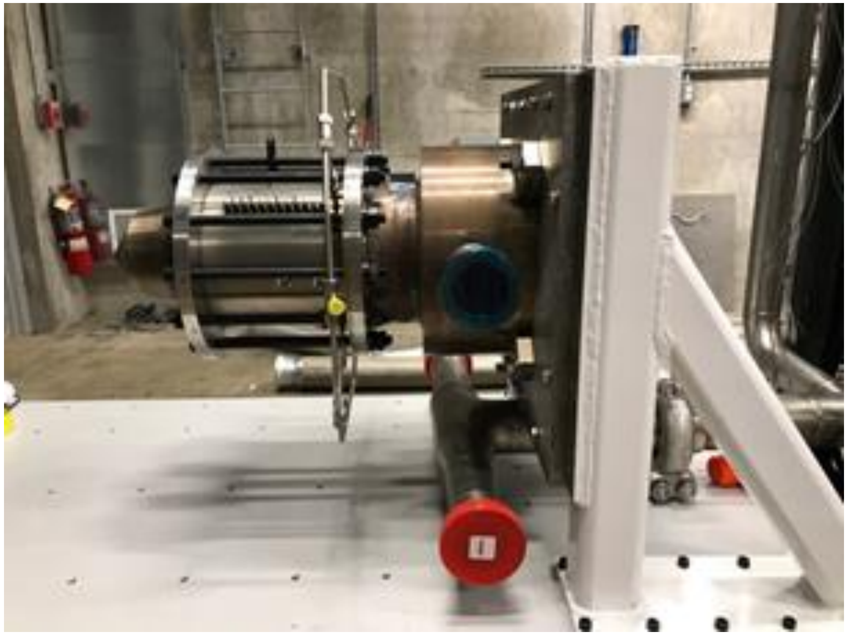
- Obtain PCB and PIV optical diagnostic measurements that are reproducible and quantitative for use in subsequent RDE performance analyses.
- Show that average stagnation pressure gain across RDE combustion chamber is greater than 2.0.
- Show that average stagnation pressure gain across RDE's injector/isolator and combustion chamber (IC-assembly) is greater than 1.86.

Task Status:

- 9.4-inch RDE is mounted in the test stand. Facility activation is underway.

Subtask 12.1 – Zucrow/APEX Buildup

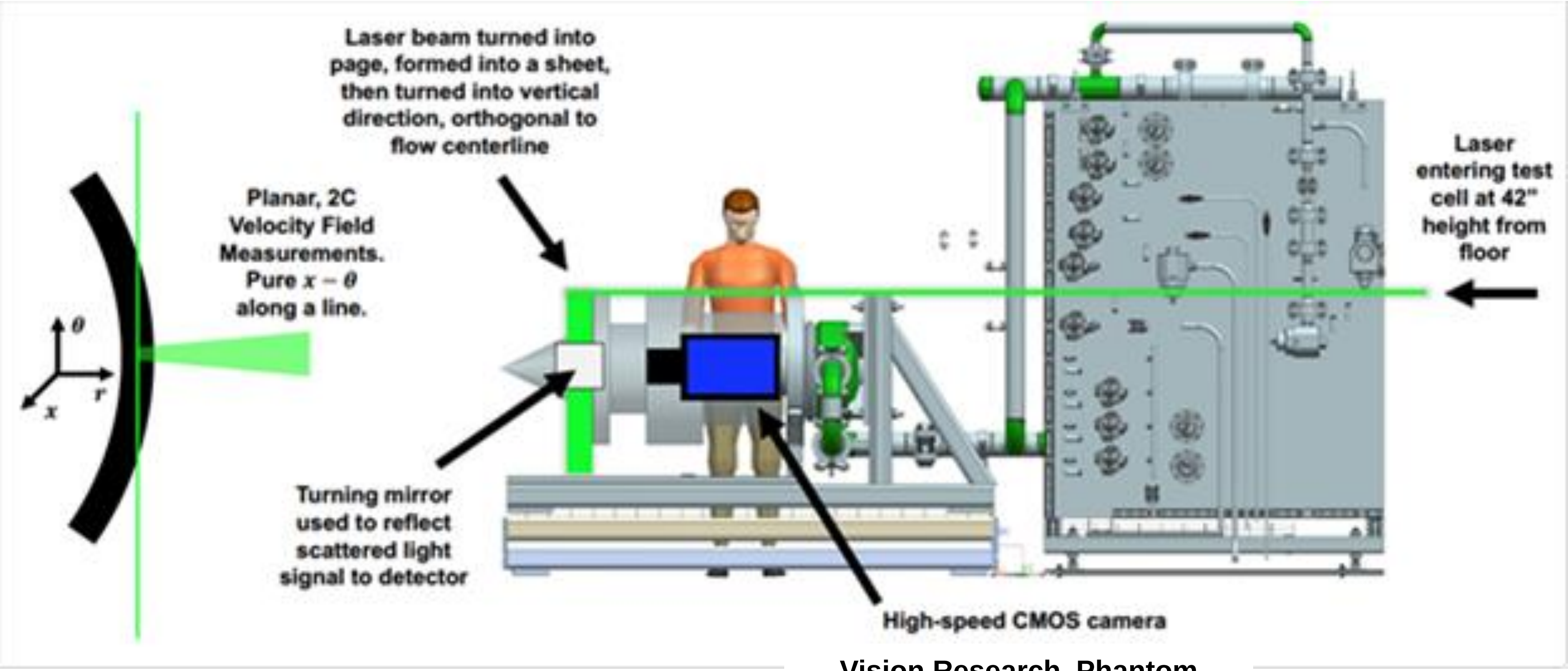
- **9.4" Diameter RDE-IC Assembly with Choke Ring mounted on Thrust Stand in APEX Test Facility**



Side View
(gas flow from right to left)

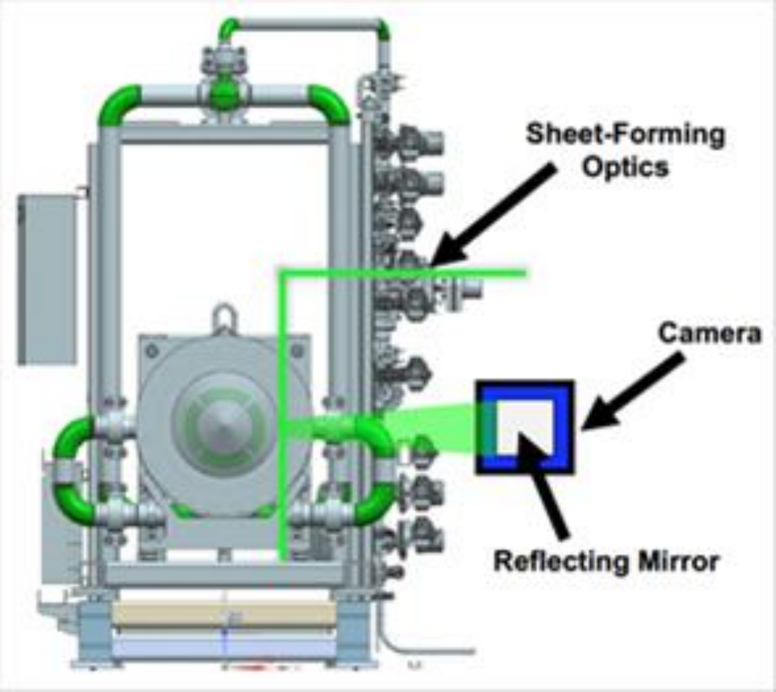
End View
(from RDE IC exit)

Subtask 12.1
APEX Test Cell with MOPA-PBL



Vision Research, Phantom v2512, ultrahigh-speed complementary metal-oxide semiconductor (CMOS) camera

Subtask 12.1
APEX Test Cell with MOPA-PBL

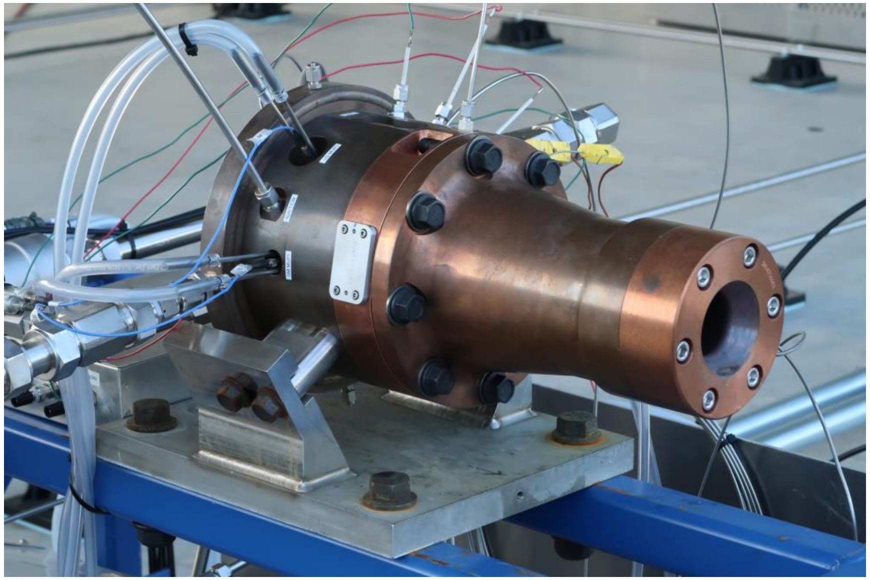


PIV Specifications

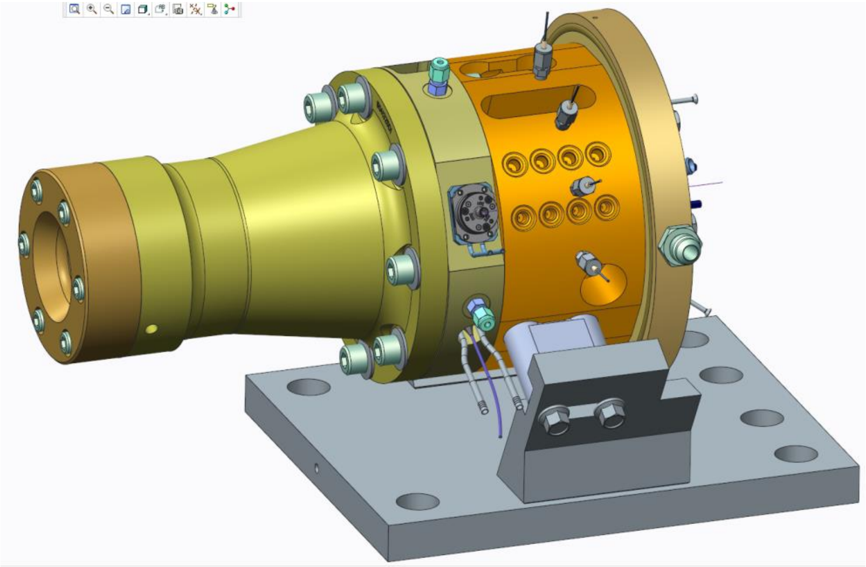
- Laser pulse-pair doublet frequency: 102.5 kHz
  - Velocity Time Series Spacing: 9.75 μs
- Temporal Resolution (Pulse-Pair Delta): 200 ns
  - Light Pulse Illuminating Duration: 5 ns
  - Light Pulse Energy: 400 mJ
- Burst Duration: 10 ms
  - Followed by 1 second cool down period
- Camera speed: 205 kHz
  - 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

Task 13 – Diffuser Risk Reduction
Southwest Research Institute

- Shane Coogan is task leader
- Set up existing AR 10 cm RDE at SwRI and operate on hydrogen and slightly enriched air
- Test diffuser configurations for design/performance data using advanced optical diagnostics from UCF



Testing of the 10-cm RDE is on-going at SwRI



Optical access spool has been delivered and installed. Laser absorption data has been obtained

Task 13 – Diffuser Risk Reduction Southwest Research Institute

Task 13.1 Summary: Optical Combustor Exhaust Flow Characterization

- Design two diffuser assemblies for testing at SwRI
- Prepare text matrix and instrumentation diagnostics requirements
- Build-up new SwRI test facility and install AR 4” diameter RDE together with diffuser assembly and upstream optical diagnostic spool
- Conduct testing on two AR diffuser assemblies and perform average stagnation pressure drop analyses across diffuser
- Apply analyses to the design of the Subtask 13.2 diffuser

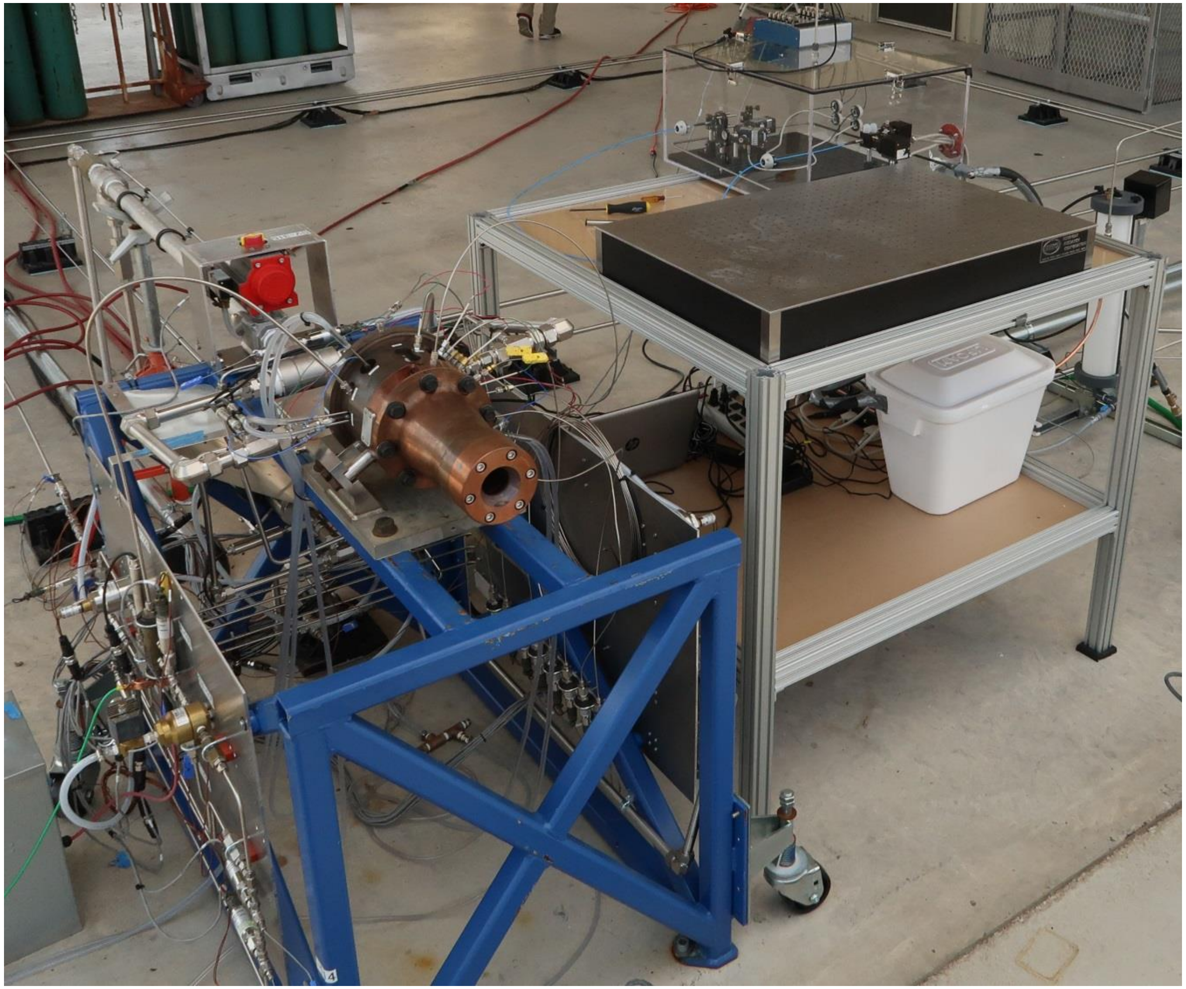
Task Goals:

- Obtain TDLAS and PIV optical diagnostic measurements that are reproducible and quantitative for use in subsequent RDE performance analyses.
- Show that average stagnation pressure loss across the diffuser is less than 20%.

Task Status:

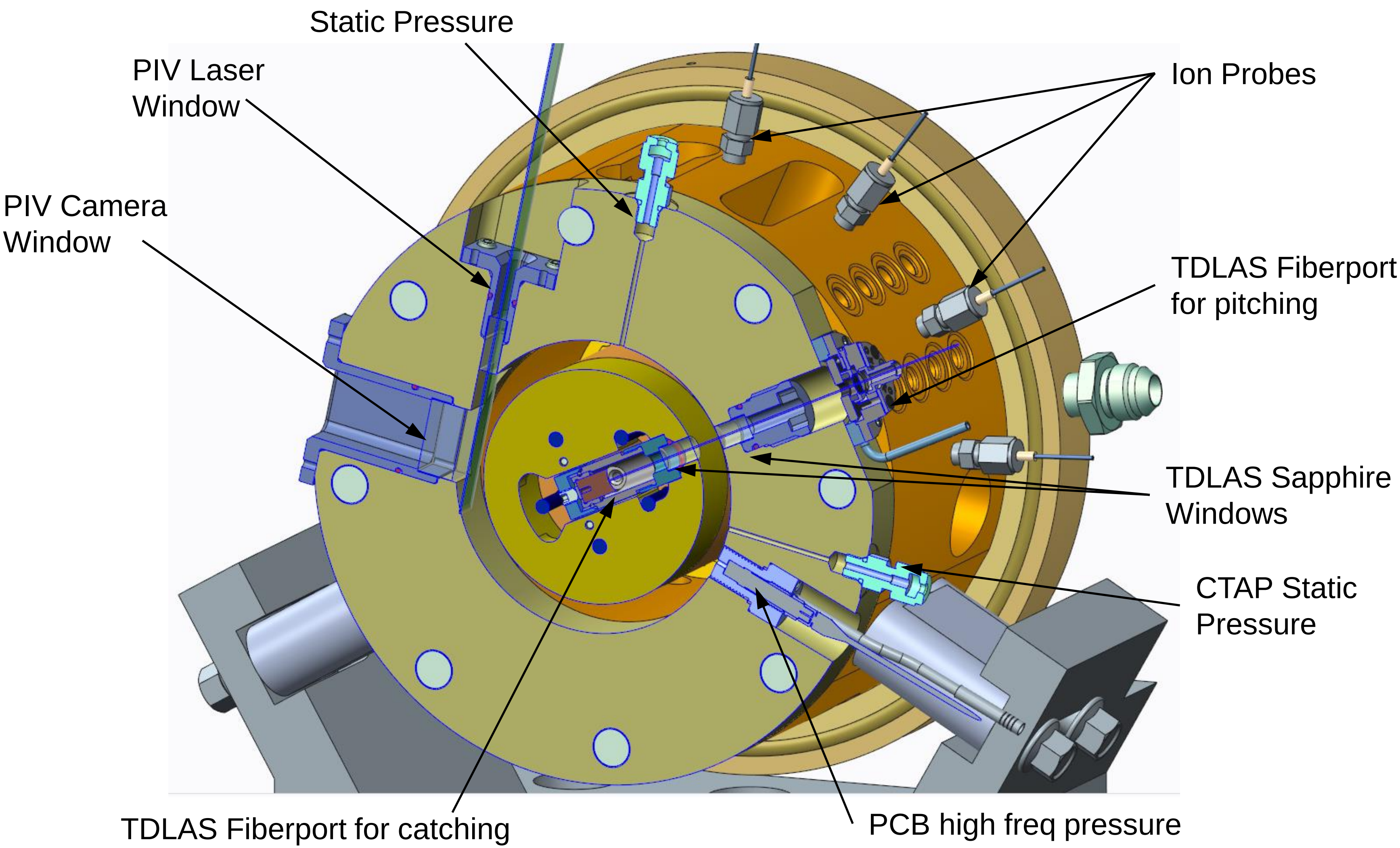
- Testing with the first two diffusers has been completed including TDLAS measurements.
- Third diffuser design complete

Subtask 13.1 – Diffuser Testing at Southwest Research Institute

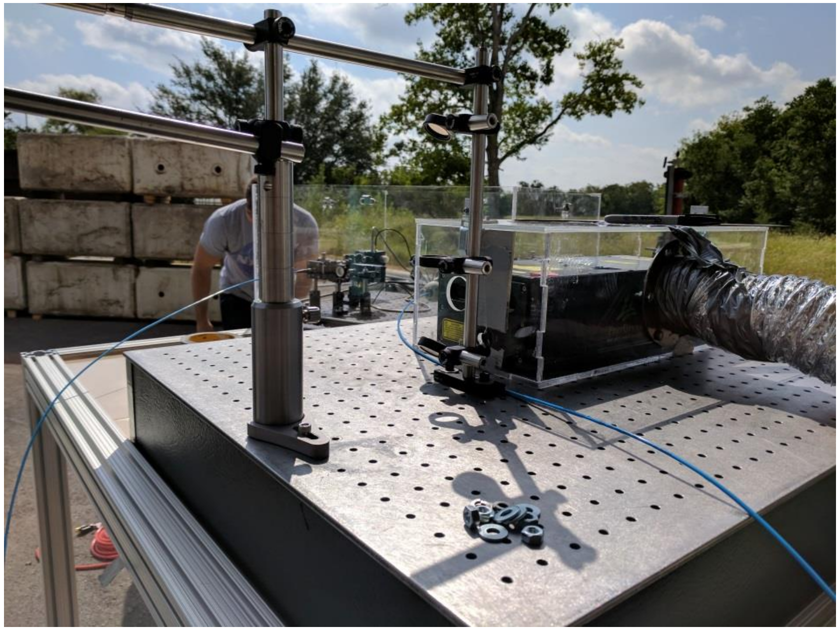


SwRI Test Stand with RDE/Diffuser Assembly and TDLAS Equipment

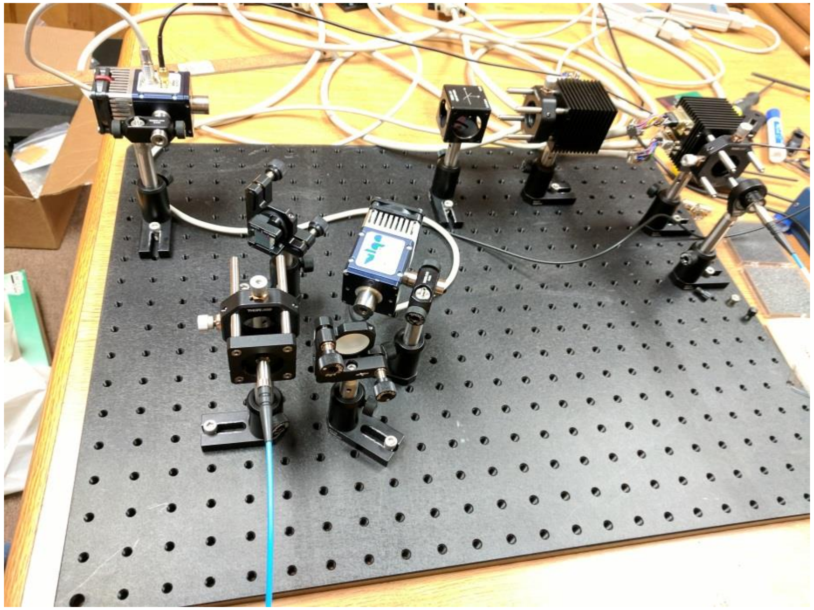
Diagnostic Access Spool for 10cm RDE at SwRI



Subtask 13.1 – Diffuser Testing at Southwest Research Institute

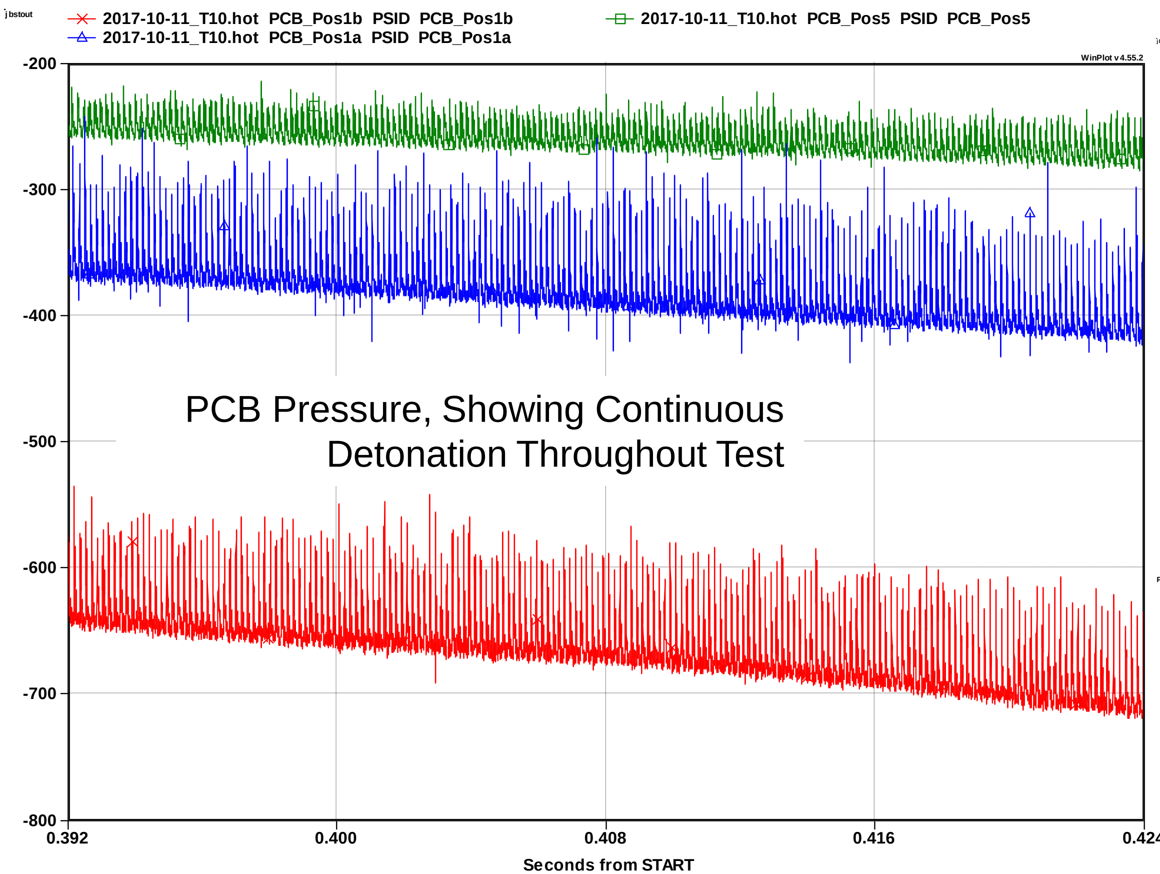


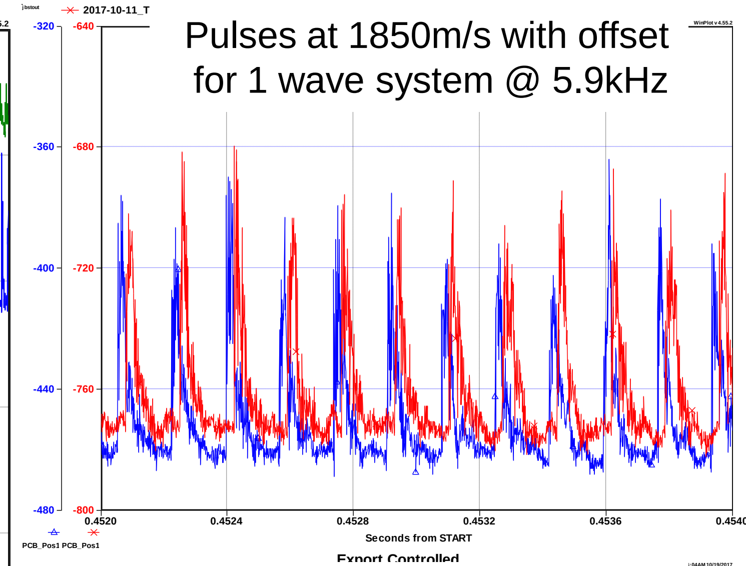
UCF's TDLAS and PIV Laser Installation at SwRI (RDE/Diffuser to left of picture)

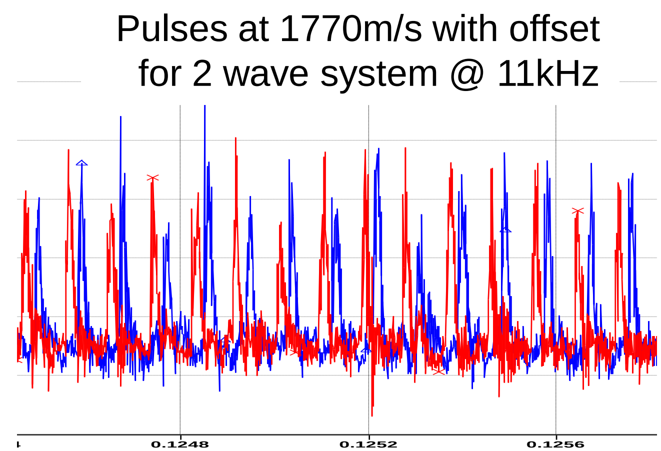


TDLAS Setup at SwRI

High Quality Preliminary Data





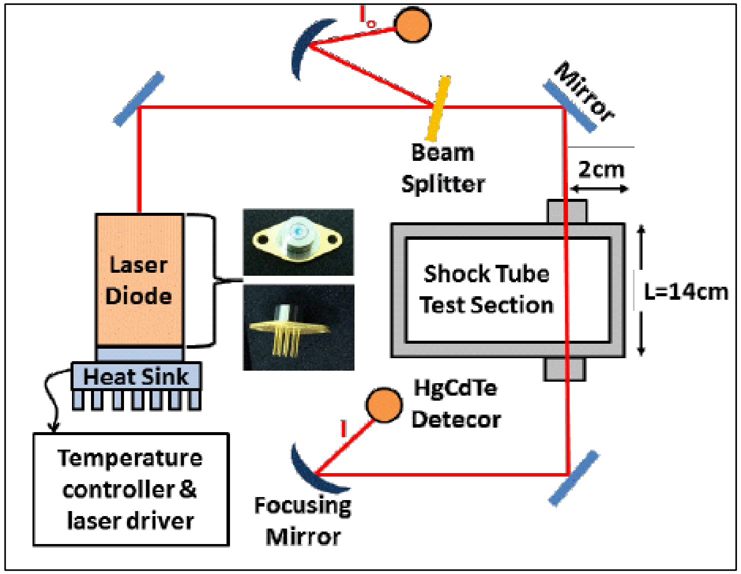


- 85 Tests with continuous detonation to date
- All tests with PCB pressure at 1 Ms/s
- 23 Tests with TDLAS measuring at 2 Ms/s
  - TDLAS able to detect individual shockwaves

Approved for Public Release

Task 15 – RDE Test Diagnostics, University of Central Florida

- Dr. Subith Vasu is task leader
- Conduct diagnostics on RDE exhaust at UA and SwRI to determine chemical species concentrations.



UCF setup for high-speed unsteady measurements of pressure, temperature, species, density and axial/tangential velocities

- Design and Fab Next Generation (NG) Optical Diagnostic Measurement System
  - 1 micro-second resolution
  - Adds species concentration measurements
  - Adds tangential velocity measurements
  - Adds phase angles among gas pressure, gas velocities, gas density, and temperature measurements
  - Measures the mass-flux averaged transient stagnation gas pressures upstream of the diffuser in-situ

  - Capable of Determining total pressure losses across diffuser or downstream ejector/mixer

Task 15 – RDE Test Diagnostics, University of Central Florida

Task 15.2 Summary: Measurement System Acquisition, Installation, and RDE Testing

- Following the recommendations from Task 15.2 procure, assemble, install, and test the TDLAS (Next Generation, NG) and PIV (State of the art, SOTA) optical high speed data acquisition systems
- Testing of these systems will be through the 4” RDE diffuser’s upstream optical spool fabricated by AR following UCF design recommendations.
- UCF’s TDLAS and PIV optics will be tested with the AR diffusers at both SwRI and UA using UCF personnel support.

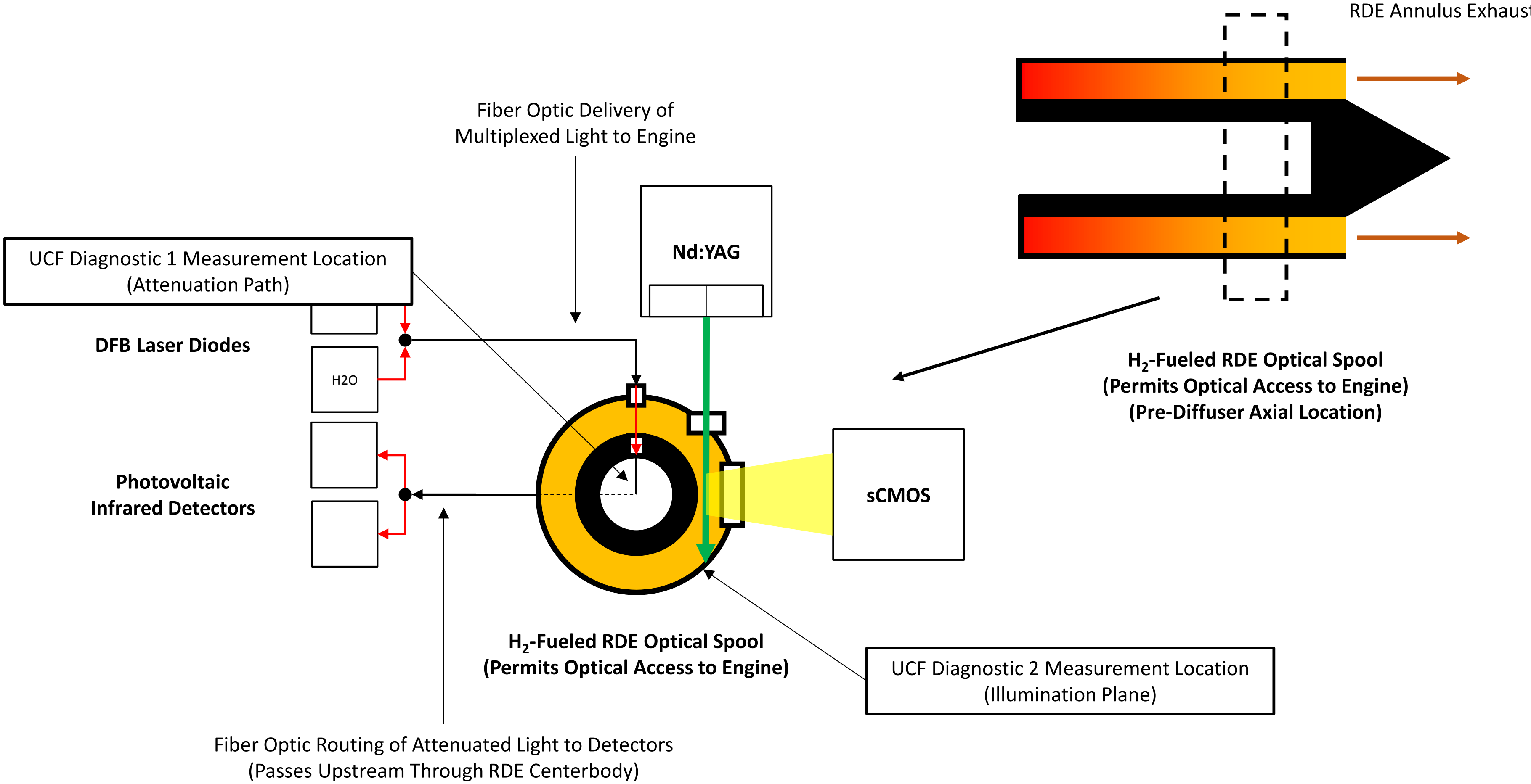
Task Goals:

- Obtain TDLAS and PIV optical diagnostic measurements that are reproducible and quantitative for use in subsequent RDE performance analyses.
- Show that average stagnation pressure loss across the diffuser is less than 20%.

Task Status:

- Diagnostics successfully activated during testing at SwRI.
- Laser systems moved to UA for combustor diagnostics

UCF Proposed Annular Measurement System



Task 15 – RDE Test Diagnostics, University of Central Florida

Next Steps

- Complete TDLAS testing with the two Subtask 13.1 diffusers at SwRI
- Start testing both TDLAS and PIV testing at UA with the two Subtask 13.1 diffusers
- Continue working the integration of the TDLAS, PIV, and PCB measurement systems to obtain better diagnostics with lower uncertainty for quantitative pressure gain determination

Summary and Next Steps

- **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 are underway using 10 cm, 21 cm and 31 cm combustors and advanced diagnostics.
    - Hot-fire testing is being performed and the University of Alabama, Southwest Research Institute and the University of Michigan concurrently.
    - 31 cm RDE is mounted in the test stand at Purdue in preparation for hot-fire testing.
  - 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.
  - Test data and analysis for PGC to be reviewed 1Q 2018.