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

DE-FE0023983

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University Turbine Systems Research annual meeting, Orlando, FL
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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%.

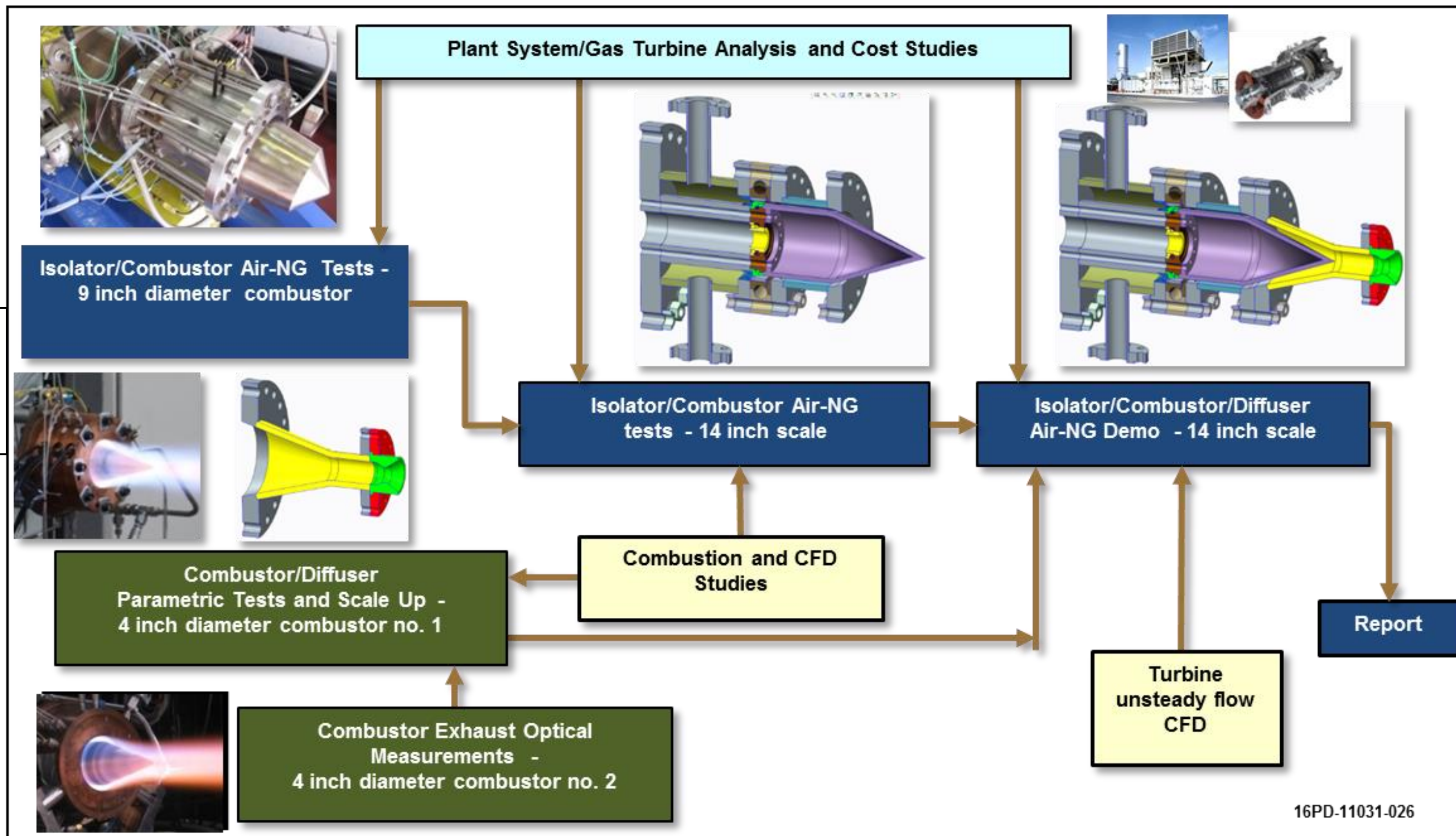
RDE Phase II Program Overview

AEROJET ROCKETDYNE

Advance Pressure Gain Combustion Technology for Turbine Applications

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

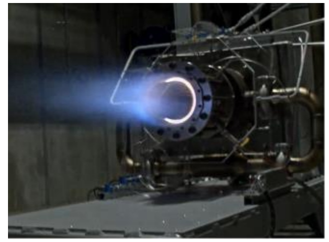
- Existing Hardware
- Separate Test Sites



Rotating Detonation Combustion for Gas Turbines Program Elements

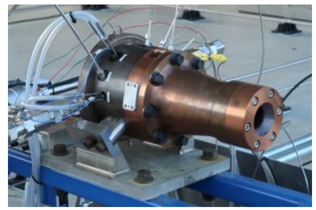
Aerojet Rocketdyne

- Project lead & system integrator



Purdue University

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

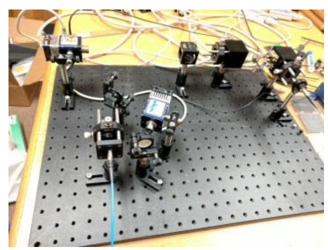


Southwest Research Institute

- 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.

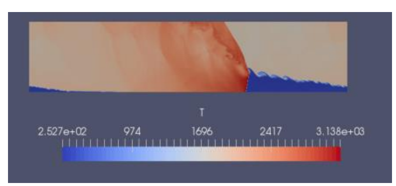


University of Central Florida

- 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

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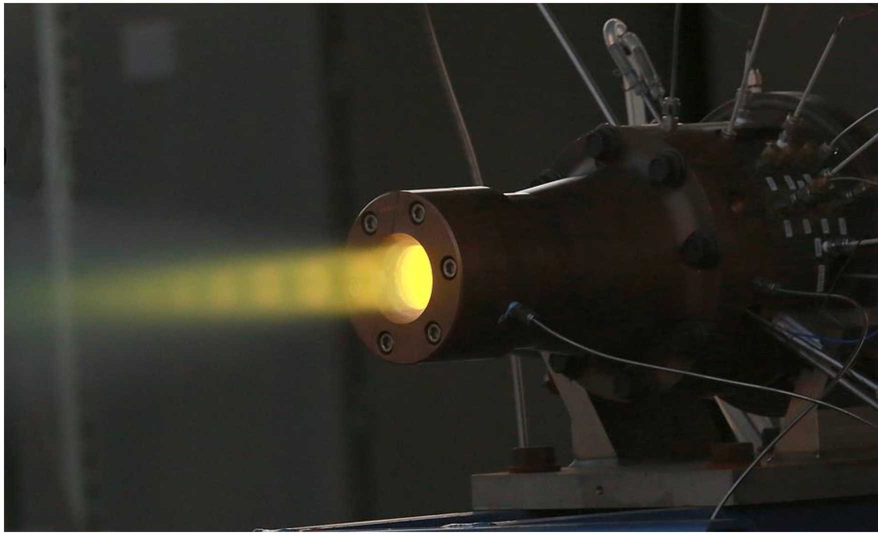
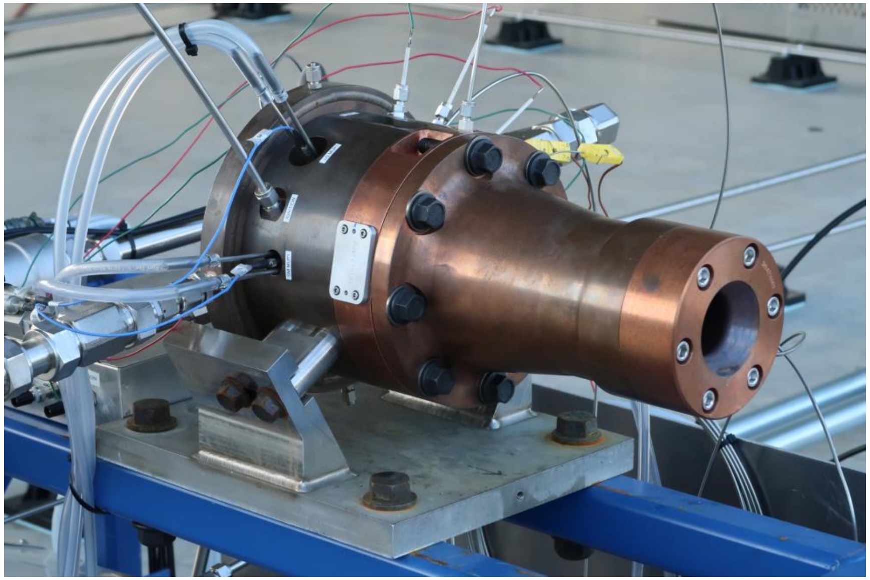
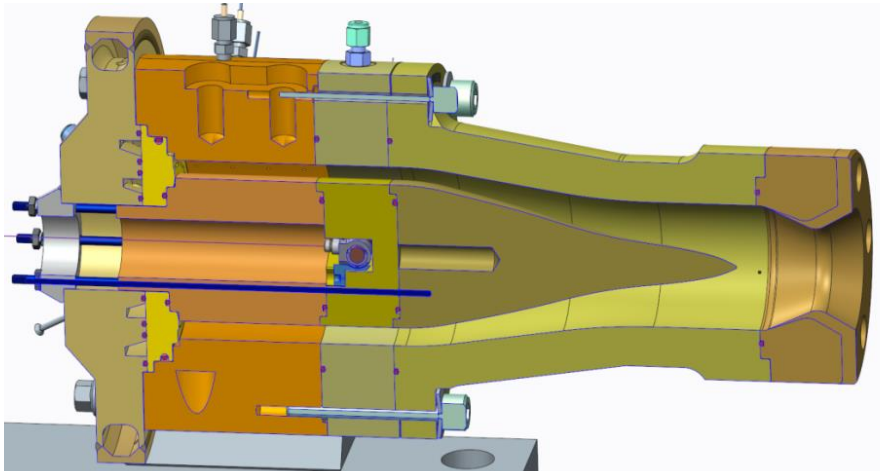
Diffuser Risk Reduction
Southwest Research Institute

- 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
- Highly instrumented chamber



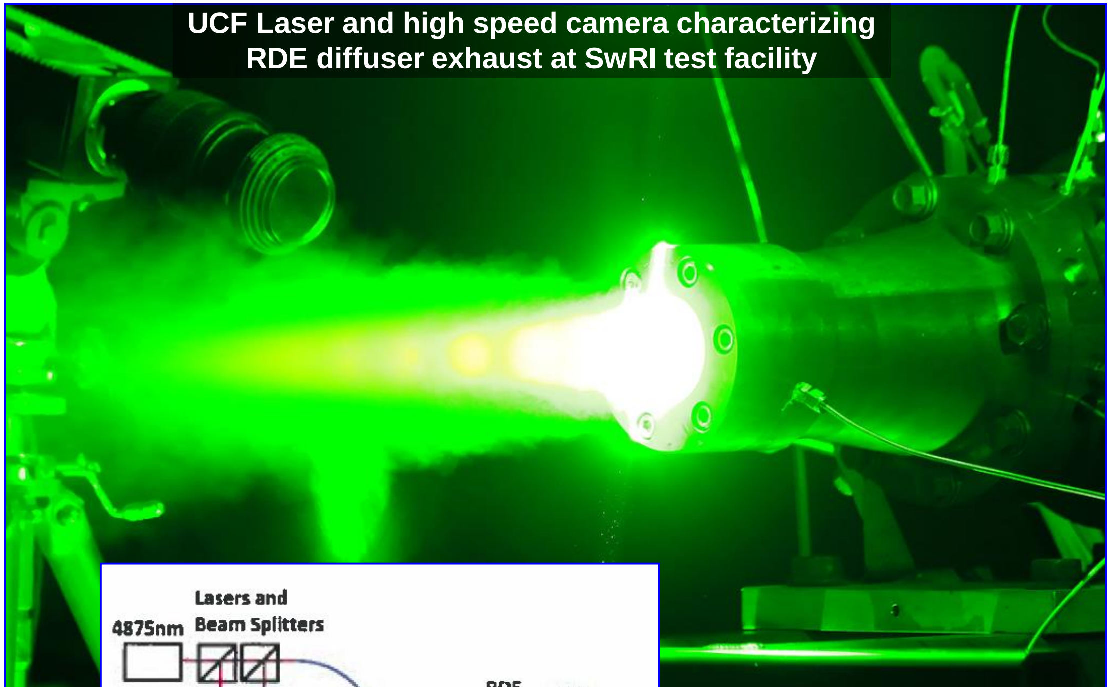


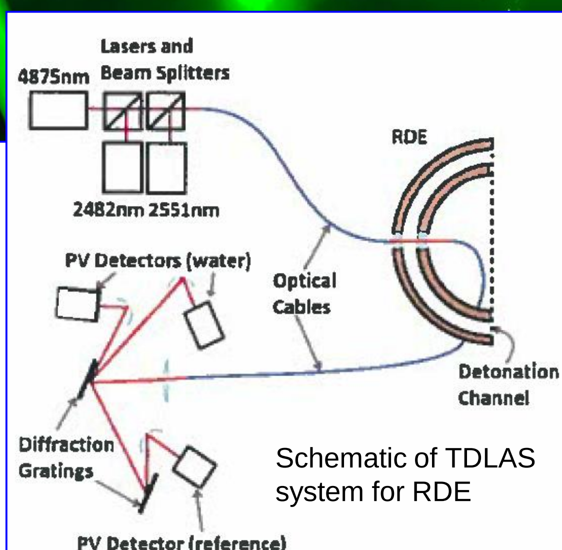
AR 4-inch RDE installed at SwRI facility with diffuser



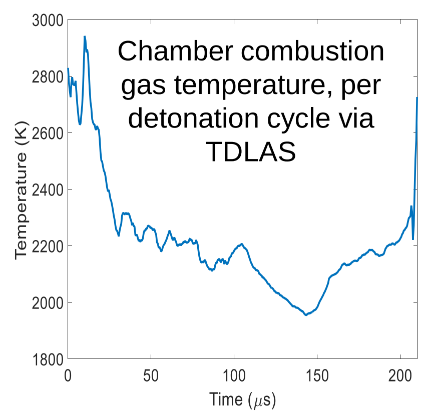
CAD cross section shows optical spools and diffuser nozzle variants

Collaborative Team Brings Advanced Diagnostics for RDE Improvements


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

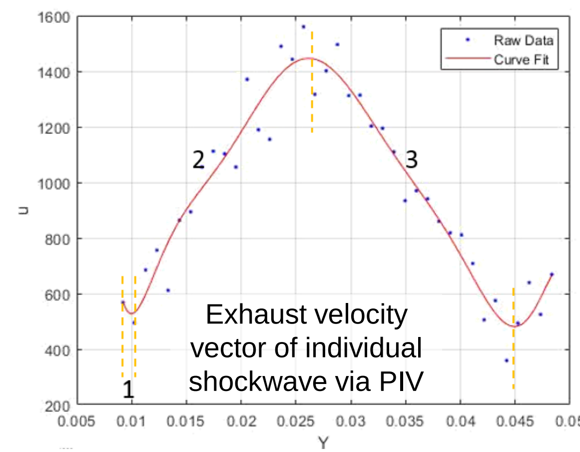


Schematic of TDLAS system for RDE



Chamber combustion gas temperature, per detonation cycle via TDLAS

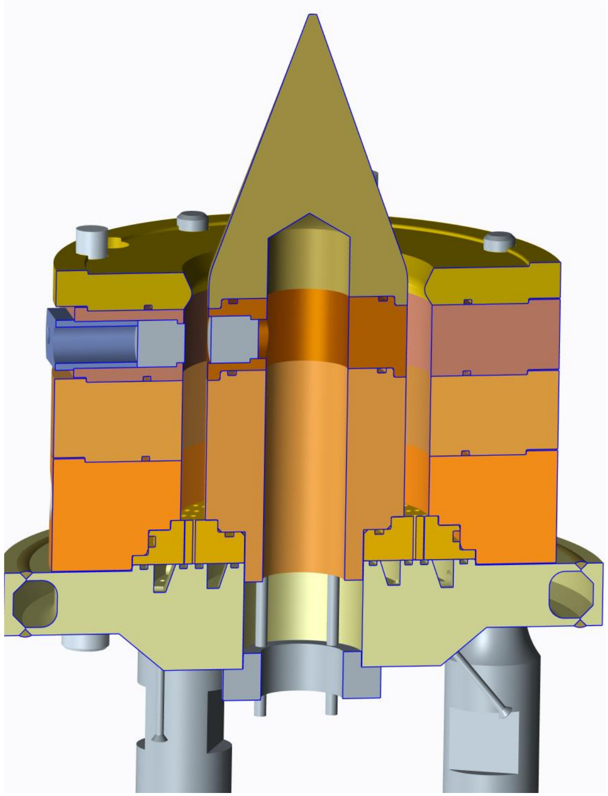
- **RDE hardware including diffuser by Aerojet Rocketdyne**
- **Southwest Research Institute (SwRI) facility set up for efficient RDE hot fire testing**
- **University of Central Florida (UCF) brought Particle Image Velocimetry (PIV) and Tunable Diode Laser Absorption Spectroscopy (TDLAS)**
- **TDLAS System capable of measuring CO (4.58um), CO2 (4.25um), water (2.48um & 2.55um), and temperature, <u>at 2MHz</u>.**



Exhaust velocity vector of individual shockwave via PIV

University of Alabama – Particle Image Velocimetry

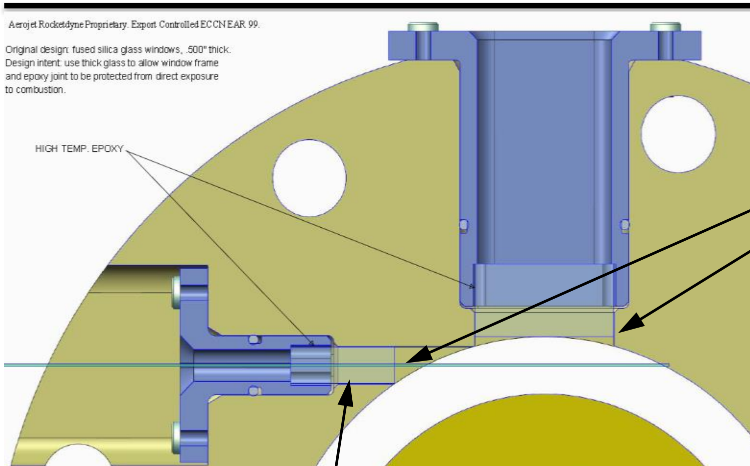
Test Site	Hot-Fire Tally	Purpose
University of Alabama (Ø4” RDE: O2+CH4) 4 configurations with 2 diffusers	85 attempts 83 with detonation 47 with PIV	Performance Testing with SOTA Optical Techniques (PIV and Chemiluminescence)



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

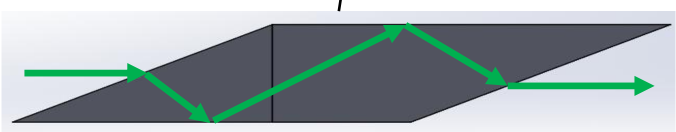
New laser allows 100kHz

Recent PIV Results with Internal Optical Spool



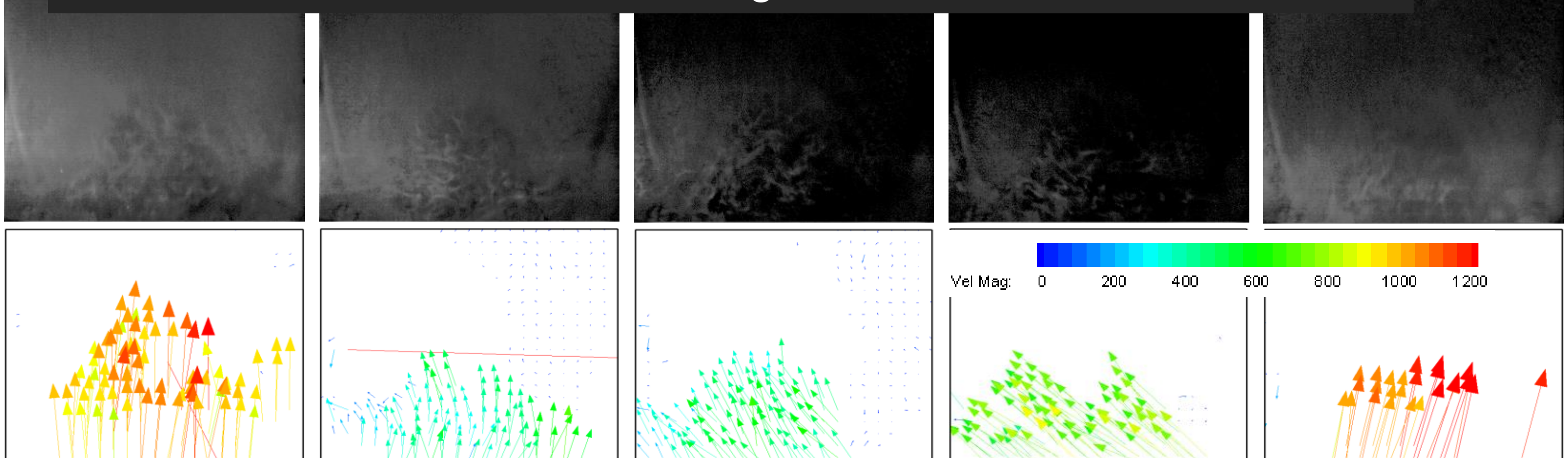
Upgrade PIV camera and laser windows to sapphire to allow in-chamber velocimetry

- Conducted external PIV measurements with improved backpressure geometry.
- Obtained PIV measurements inside the RDE at 30kHz.
- Limited by window damage



Parallelogram window shape eliminates recirculation zone

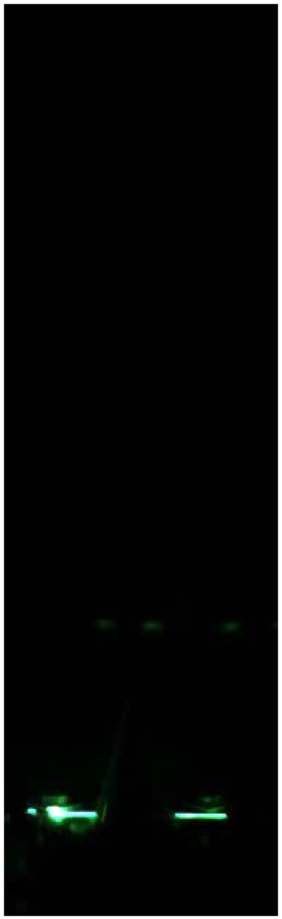
Results show much better agreement with simulations



Optical Diagnostic Testing was Recently Completed at the University of Alabama

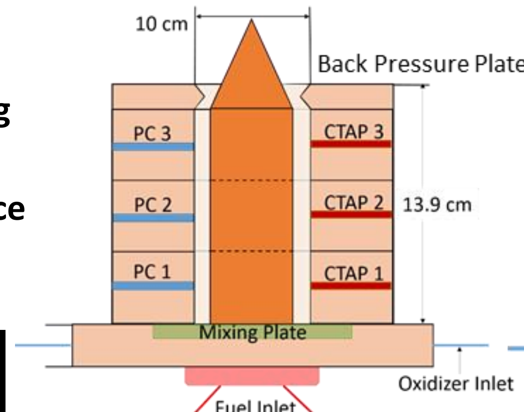
- Apply Time-resolved optical diagnostics to investigate RDE flow and combustion fields
  - Particle Image Velocimetry (PIV),
  - OH* chemiluminescence,
  - high-speed imaging, ion-probes,
  - rainbow schlieren deflectometry
- Operate RDE at high-pressures using methane fuel
- Investigate diffuser designs to reduce flow fluctuations

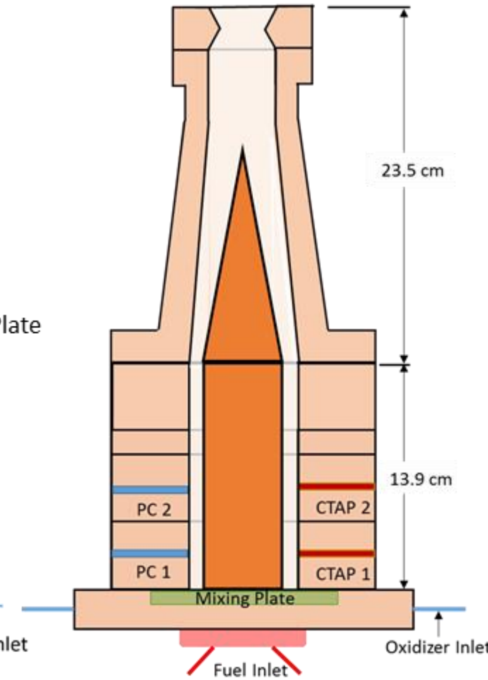
COMBUSTION LABORATORIES
THE UNIVERSITY OF ALABAMA
LOW EMISSIONS • HIGH EFFICIENCY • FUEL FLEXIBILITY

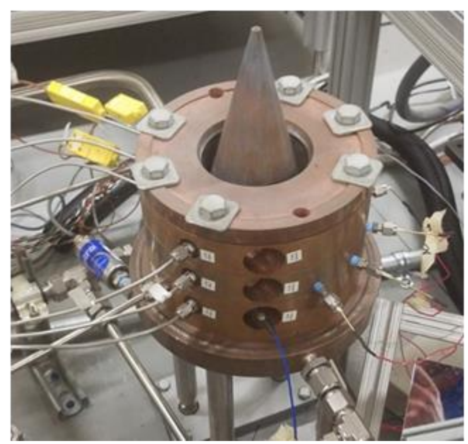


Side View:
Acquired at 30000 fps

Top View:
Acquired at 186000 fps



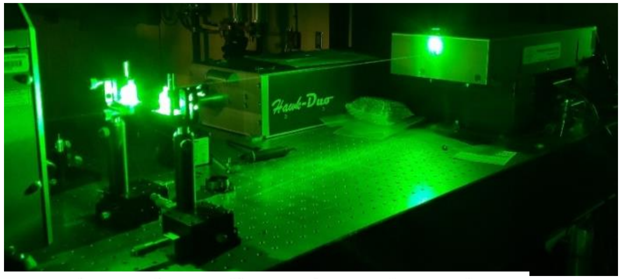


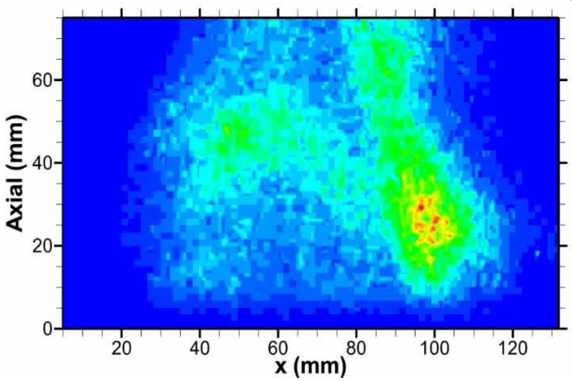


RDE with Back-Pressure Plate

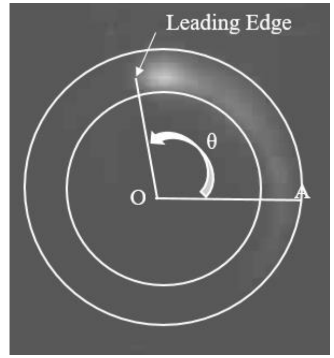
RDE with a Diffuser

Diffuser Is Effective at Reducing Circumferential Velocity Unsteadiness

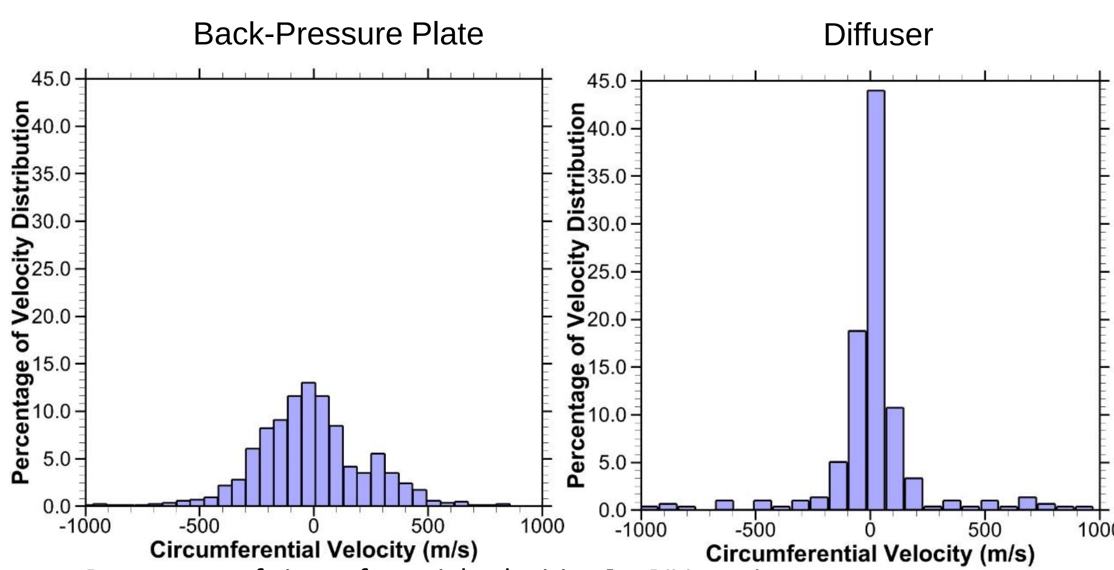




OH* Chemi. images at RDC exit, 30 kHz



Optical technique to determine wave speed



Percentage of circumferential velocities for PIV results

- Back-pressure plate case - Circumferential Velocity: 50% of velocity vectors fall within ±200 m/s
- Diffuser Case - Circumferential Velocity: 80% of velocity vectors fall within ±200 m/s indicating reduced flow fluctuations

<u>Optical Diagnostic Capabilities:</u>

- **Particle Image Velocimetry (PIV)**
  - **Up to 100 kHz, < 1 μs Δt**
- **OH Planer Laser Induced Florescence (PLIF)**
- **OH* Chemiluminescence**
- **Rainbow Schlieren Deflectometry**
- **Thermoacoustic Analysis**
- **Phase Doppler Particle Analysis (PDPA)**
- **2-Color Pyrometry**

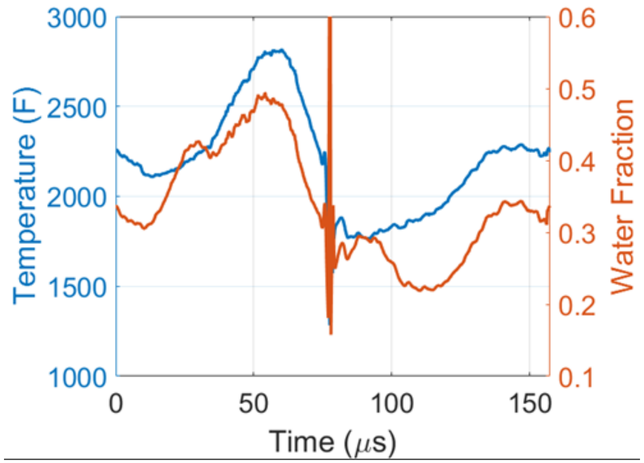
University Of Central Florida

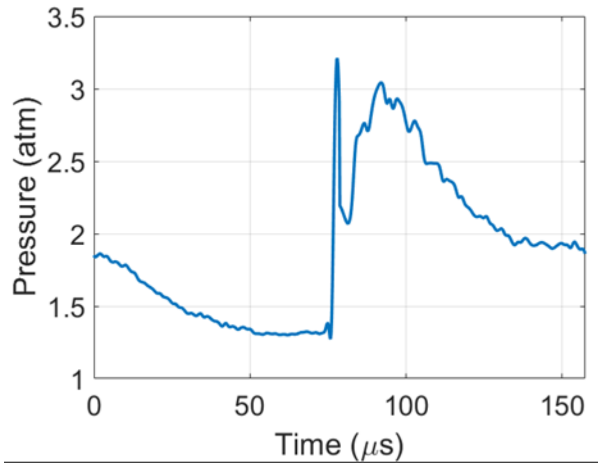
Results: CH_4-Air/O_2 Engine

AEROJET ROCKETDYNE

- Temperature drop stalls after shock then begins to climb ~15μs later (marked by a broad pressure peak and a secondary Schlieren spike).
- Water increase corresponds with temperature increase.
- Temperature much lower than expected.

- Incomplete combustion during detonation stage, resulting in lower temperatures and a secondary combustion event initiated by the oblique shock wave.

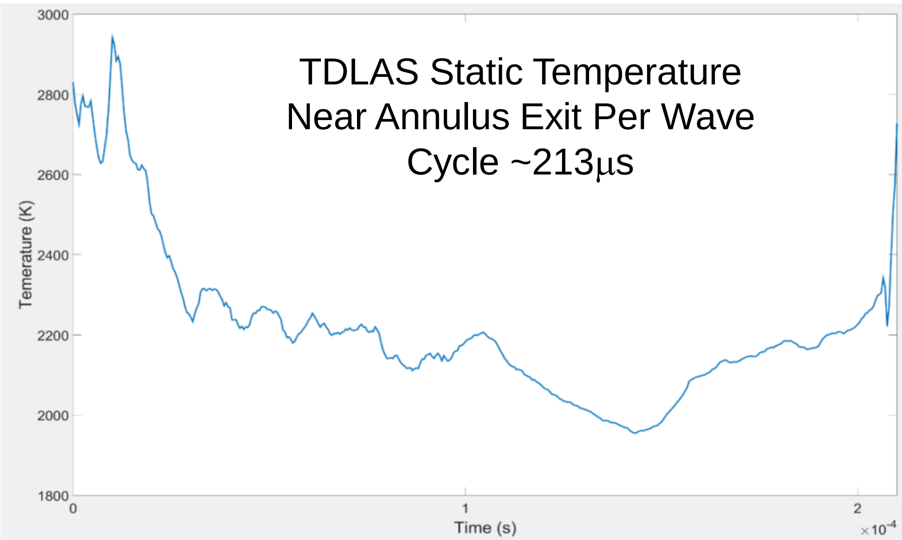


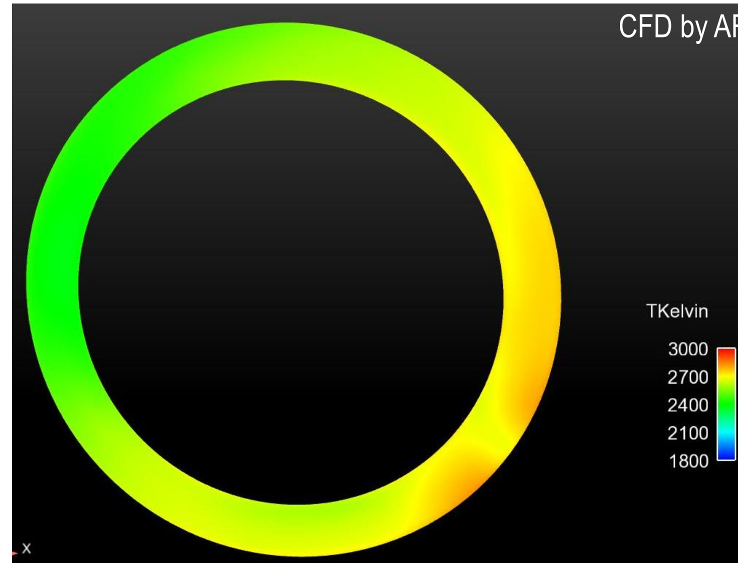


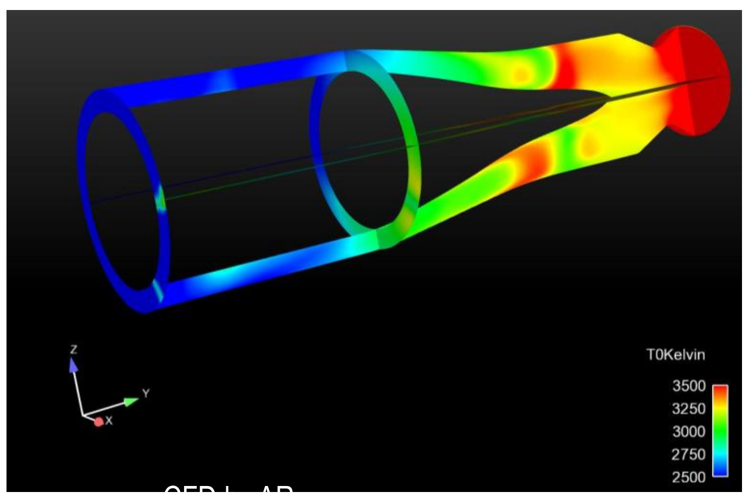
Agrees with findings from UM and AR CFD, reason for reduced performance

ϕ	$\dot{m}_{CH4}$	$\dot{m}_{air}$	$\dot{m}_{O2}$	$\dot{m}_{total}$	Nozzle
1.03	0.103	0.225	0.351	0.679	#1

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

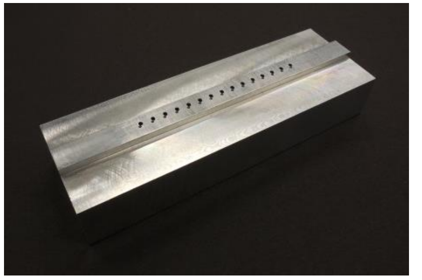


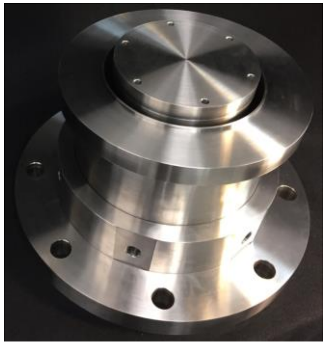




RDE experimental program at UM

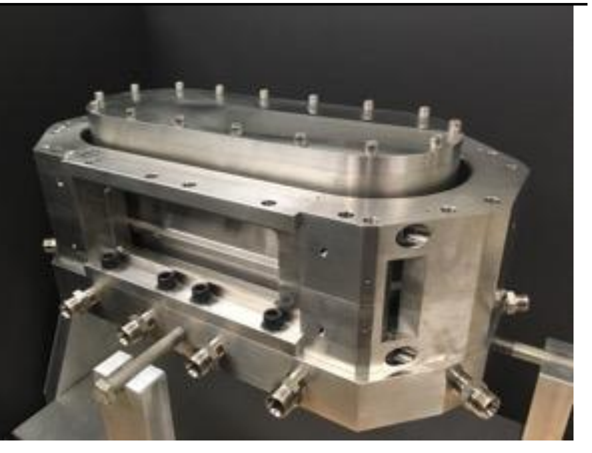
- **Injector sector subassembly**
  - Unwrapped sector of RDE injector
  - Unit problem studies
    - Mixing effectiveness
    - Shock-induced mixing



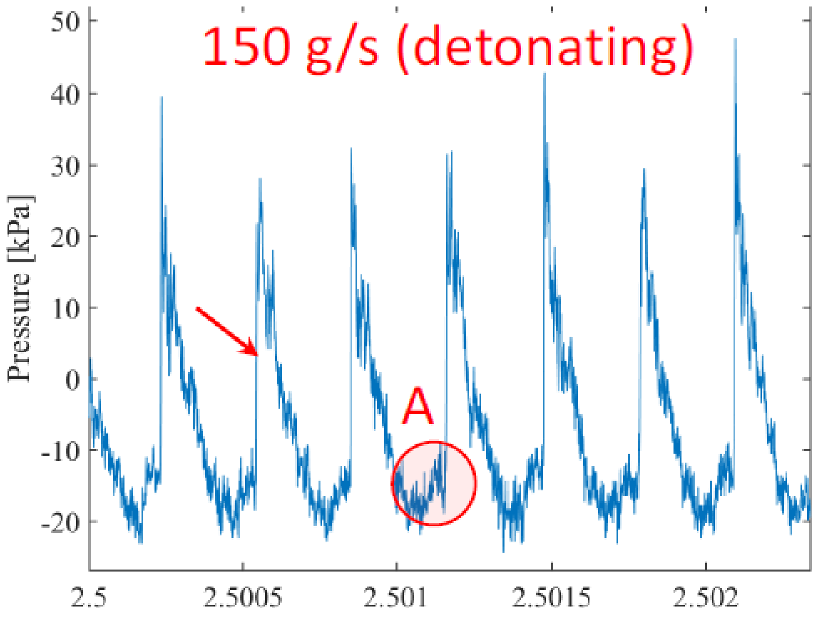


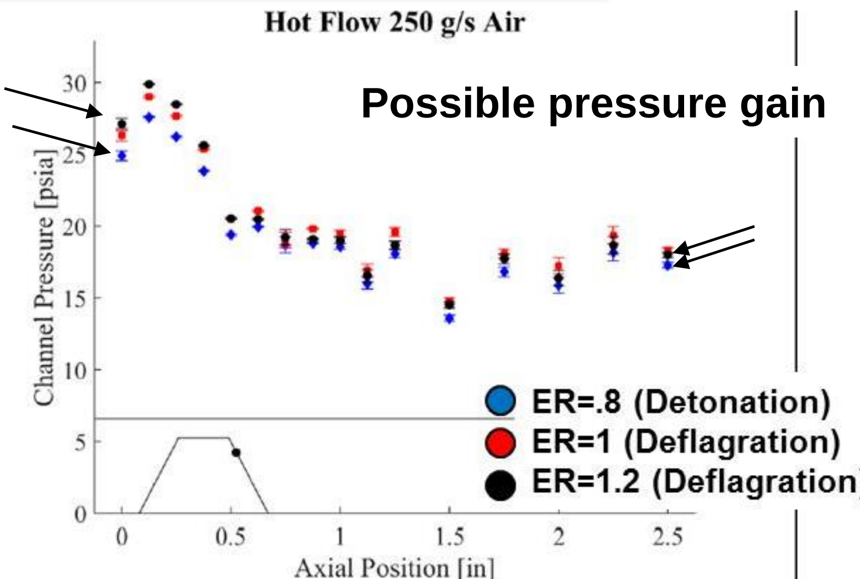
- **Round RDE (6” diameter)**
  - Operational with H_2/Air, various flow rates and equivalence ratios
  - Expanded to operate with multi-component fuels (hydrocarbon blends)
    - Working toward stabilizing HC blends (syngas and NG applications)
  - Instrumentation development is continuously ongoing
    - Combination imaging and quantitative measurements of state

- **Optical RDE (Race-Track RDE)**
  - Fundamental physics in RDE-relevant flowfield
  - Equivalent to 12” round RDE
  - Used for flowfield measurements using laser diagnostics under RDE relevant conditions
    - Imaging for mixing, detonation structure, injector response studies



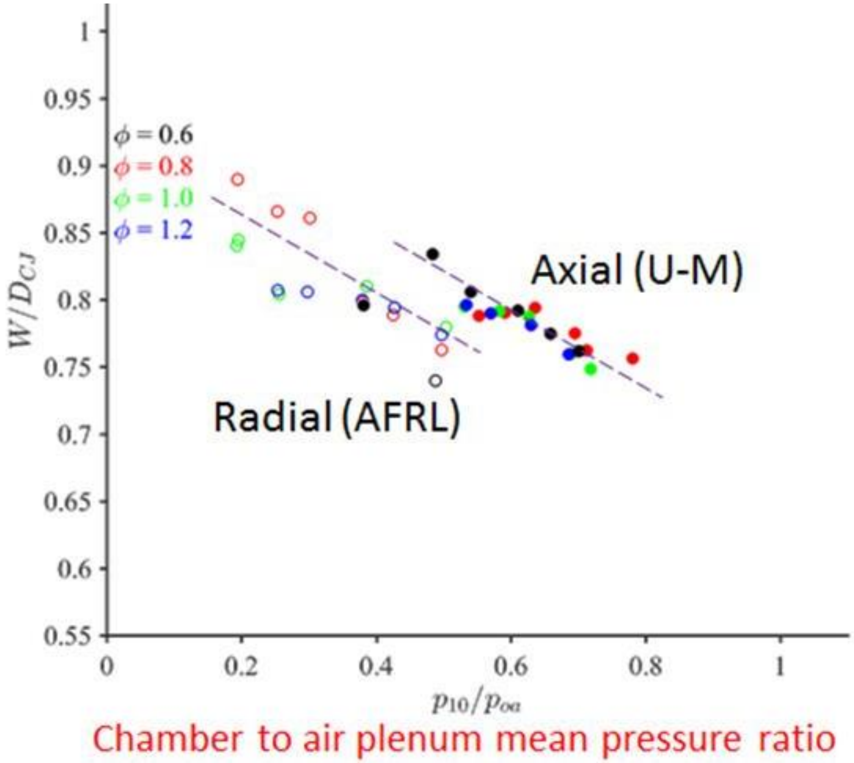
University of Michigan (UM) Hot-Fire Testing Provides Data For CFD Model Correlation

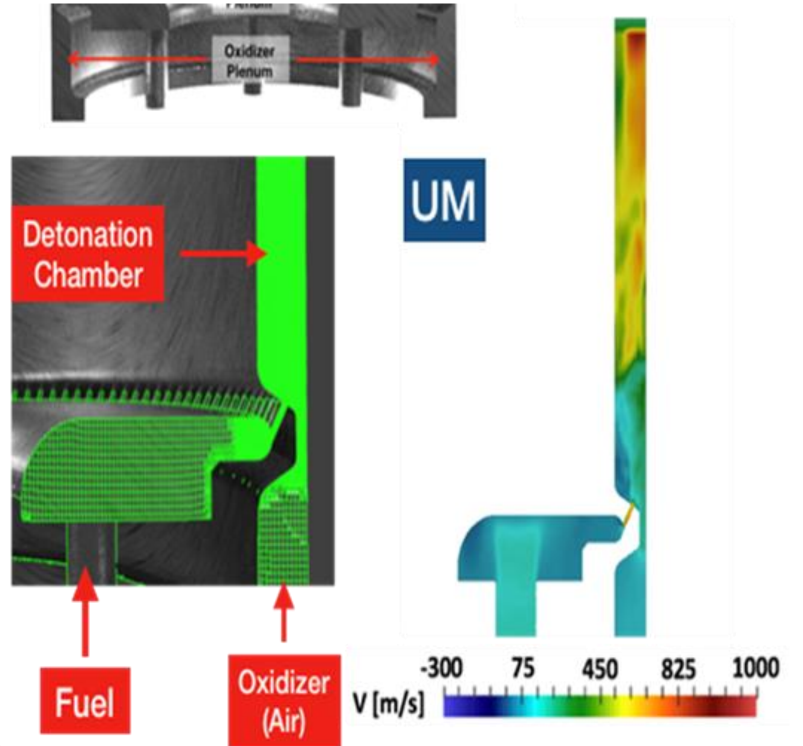




- Pintle Injector Detonation: Similar to AR System
- Instream Measurements to Provide Validation/Input to Kinetics/Turbulence Modeling
- Testing to Date Shows Evidence for Annulus Pressure Gain: Lower Manifold Pressure with Detonation for Fixed Back Pressure

Test and LES Combustion CFD Conducted for UM Pintle, AR-like Injector Configuration



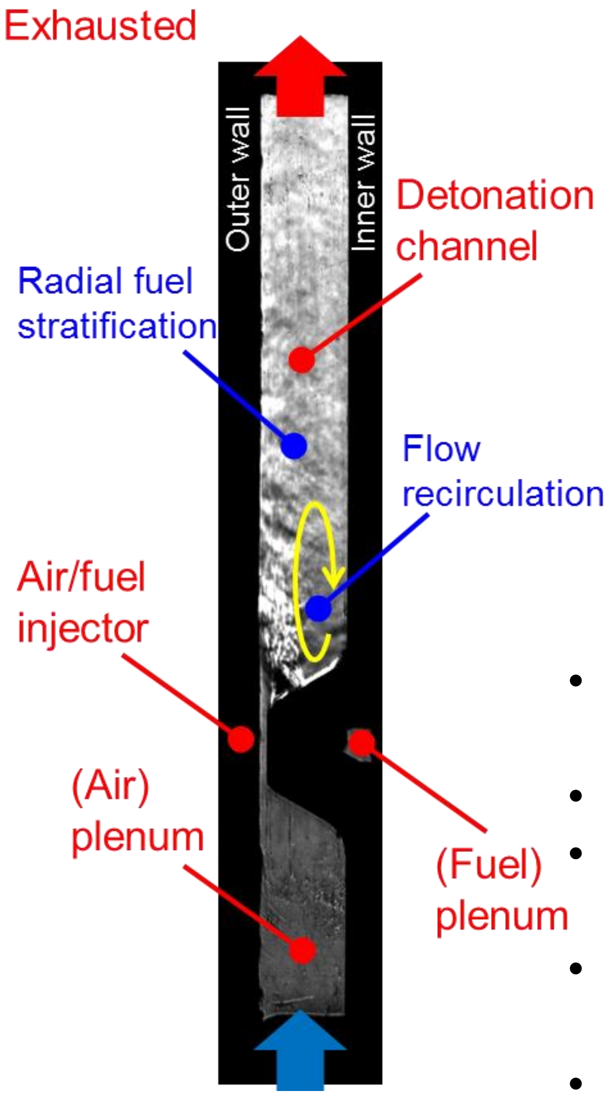


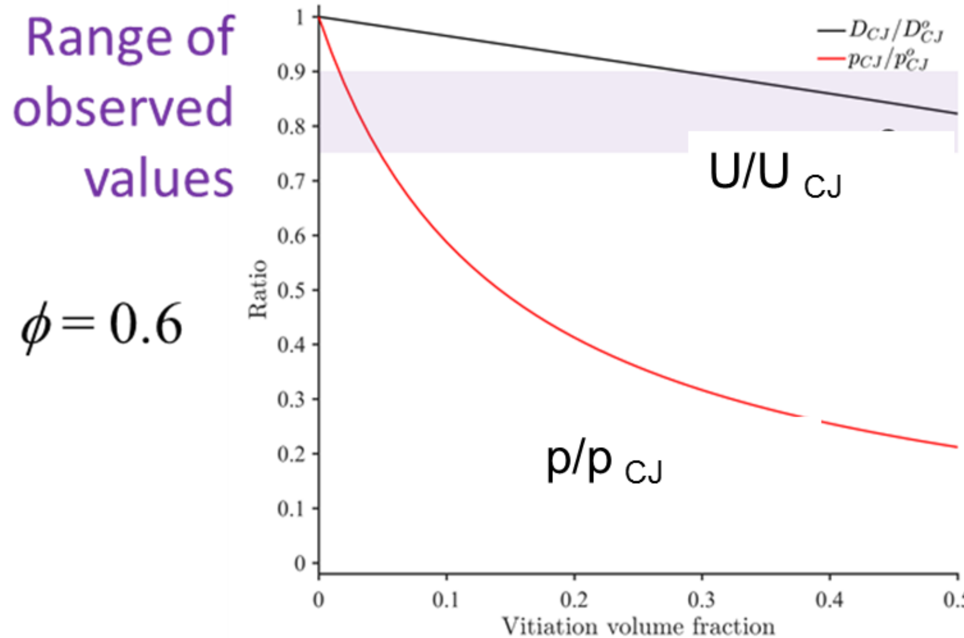
- Constricted ~5:1 and Open ~2.5:1 Inlets
- Axial (AR-Like) Outperforms Radial Injector at Similar Contraction
- OH PLIF, OH Emission Spectroscopy, Schlieren for Racetrack Design
- CTAP Measurements Suggest Open Inlet May Enable Pressure Gain

Constricted Inlet Test Compared to LES CFD

- Wall Pressures Compare Favorably with Pintle Test Measurements

UM Test and CFD Suggest Vitiation Key Driver in Performance Reduction





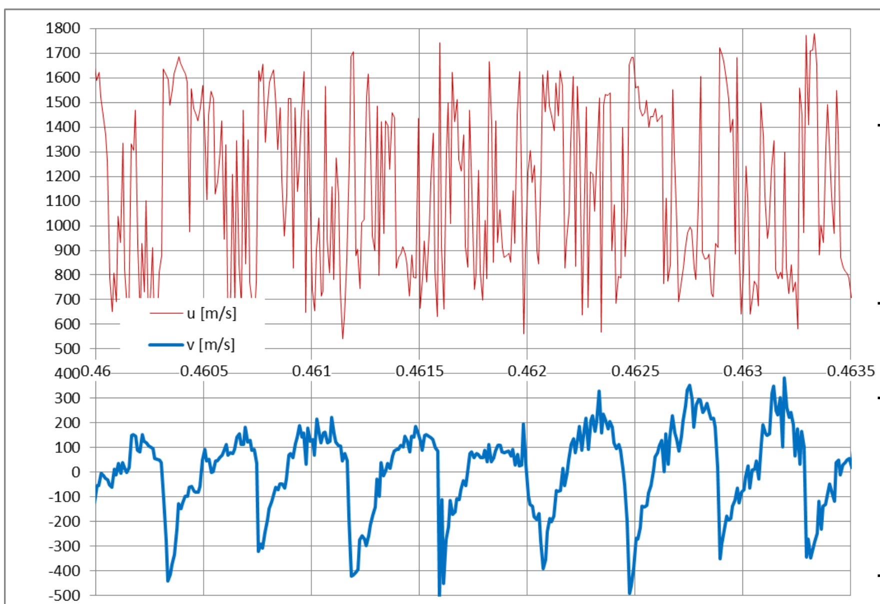
- Fuel Stratification and Separation Regions Trap Products from Previous Detonation Cycle
- Seen in Both UM Test Visualization and CFD
- Cause of Vitiation Contributing to Lower Pressure Rise and Wave Speed—Lower Performance
- Parasitic Combustion Wave Interference Also Diminishes Performance (Ref: UCF)
- Present for H_2/Air—AR Results Suggest Larger Issue for CH_4/Air

Purdue University

PIV Setup for 9.4” RDE

AEROJET ROCKETDYNE

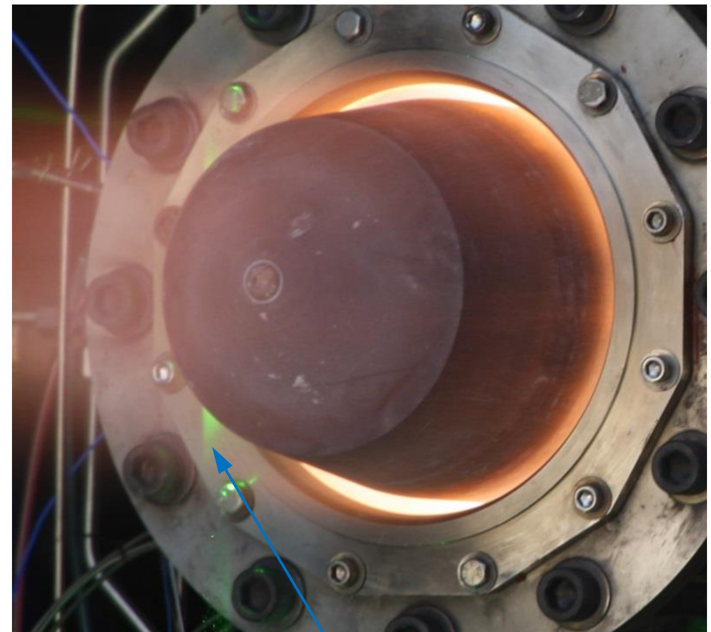
- Laser pulse-pair doublet frequency: 102.5 kHz
  - Velocity Time Series Spacing: 9.75 µs
- Temporal Resolution (Pulse-Pair Delta): 200 ns
  - Light Pulse Illuminating Duration: 5 ns
  - Light Pulse Energy: 400 mJ
- Burst Duration: 10 ms
  - Followed by 1 second cool down period
- Camera speed: 205 kHz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



Axial Component

Tangential Component

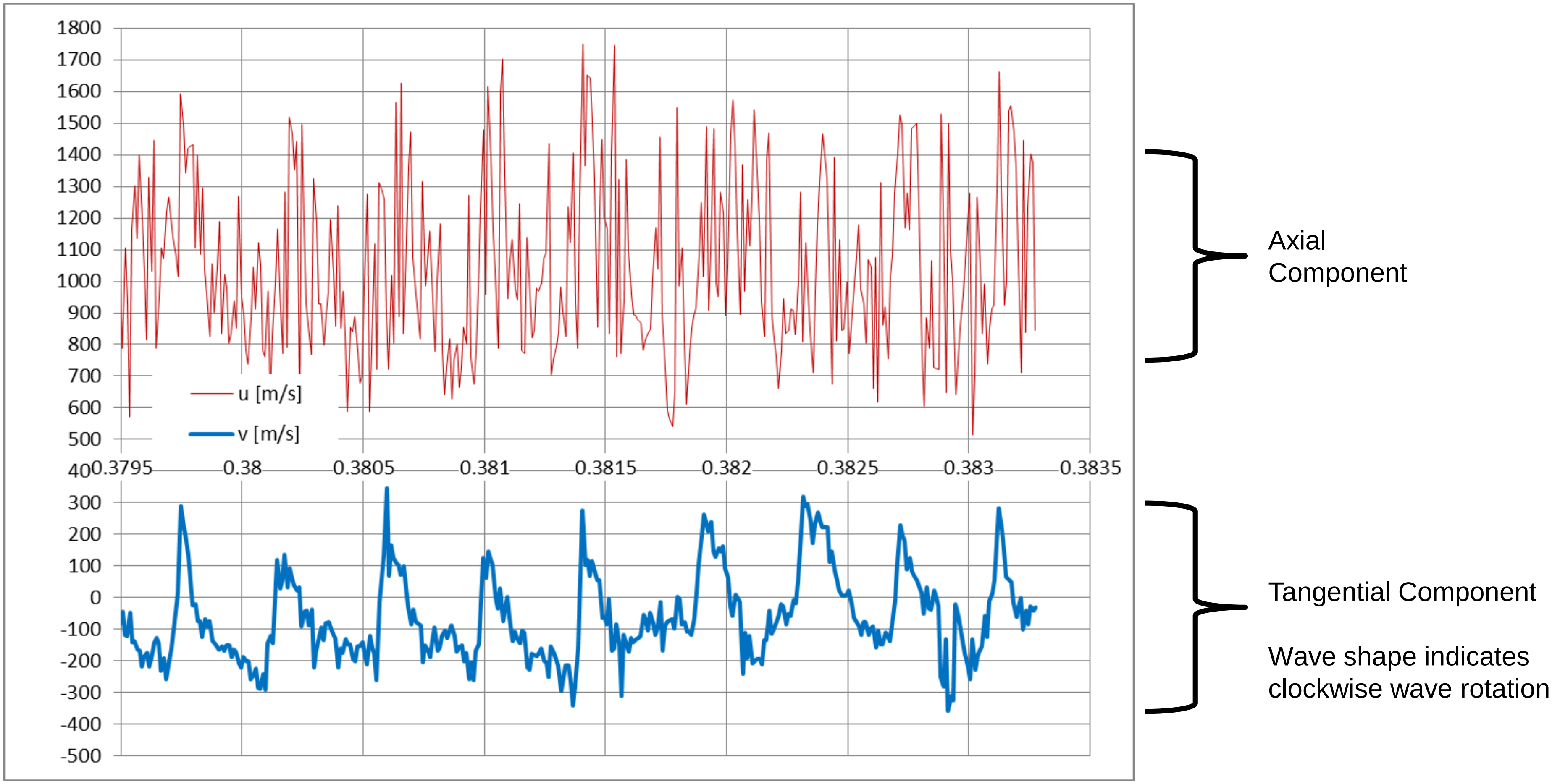
Wave shape indicates counter-clockwise wave rotation



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

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

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



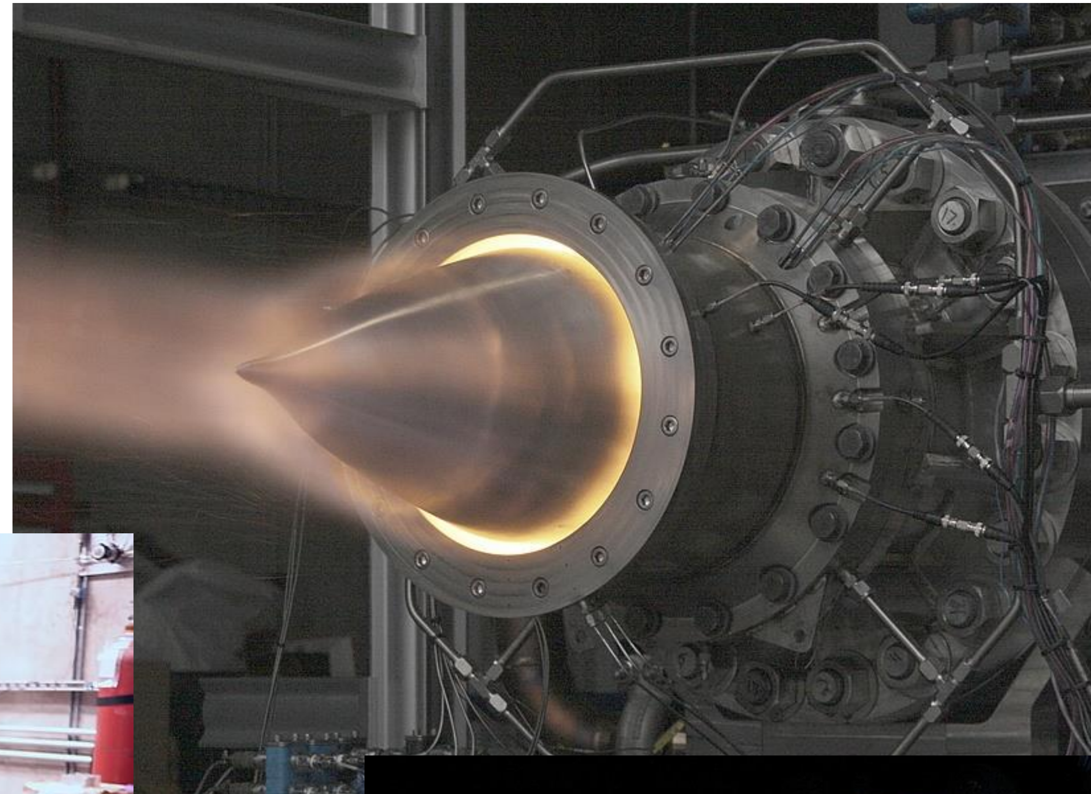
Purdue 100kHz system provided unprecedented temporal resolution, allows over 40 samples per 430μs detonation cycle

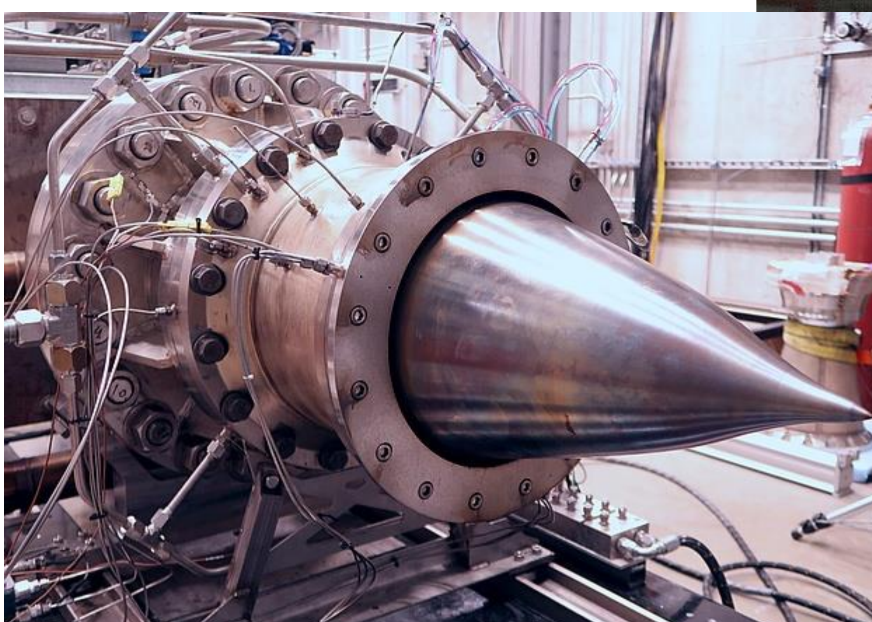
Engineering Scale 13.4" RDE Testing at Purdue University

- Purdue Zucrow Labs
- December 2018 – May 2019

- Natural gas + air
- 180 tests
- 113 tests w/ detonation behavior

- Modular hardware
- 20 injector/inlet/nozzle hardware configurations tested to date





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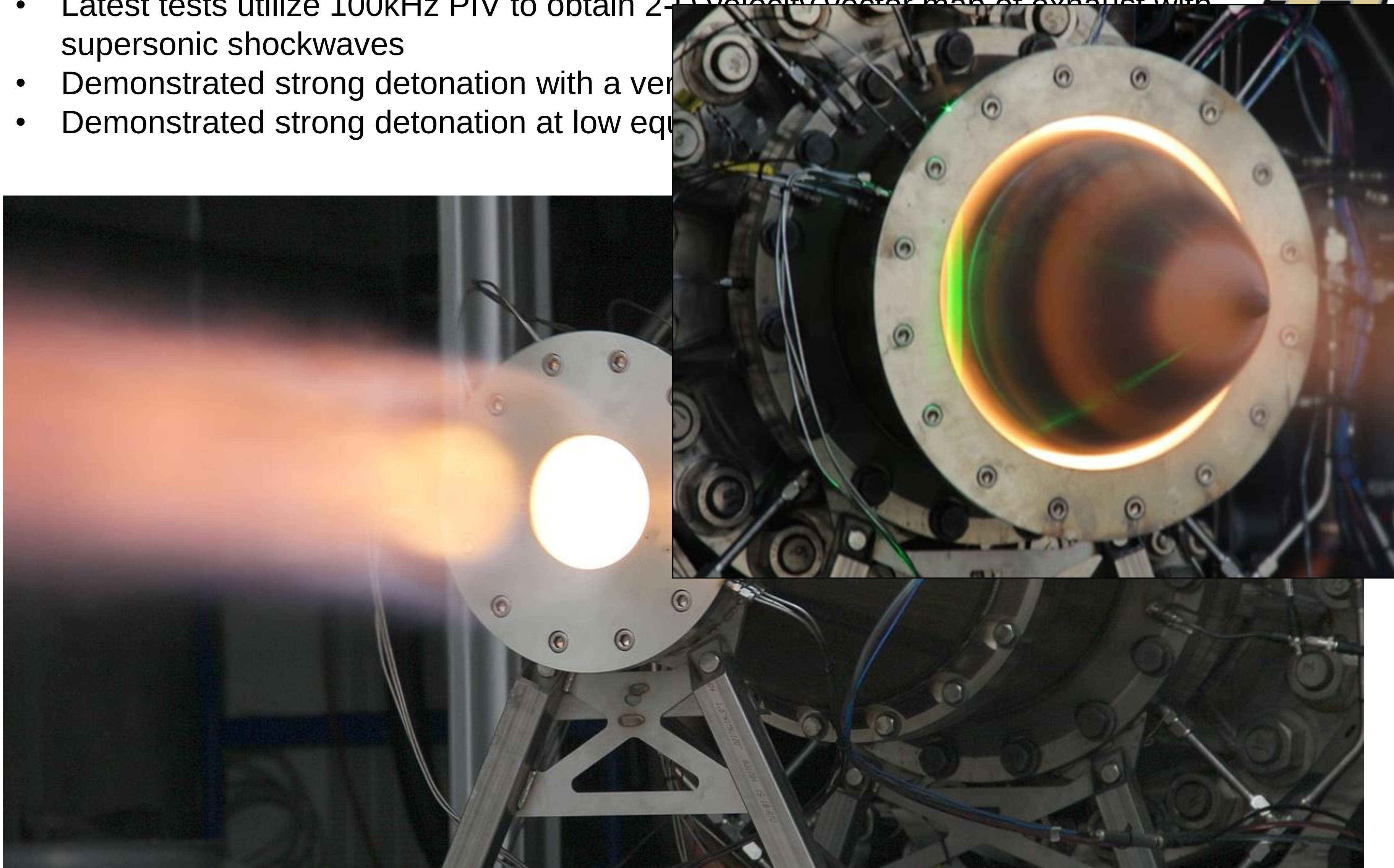
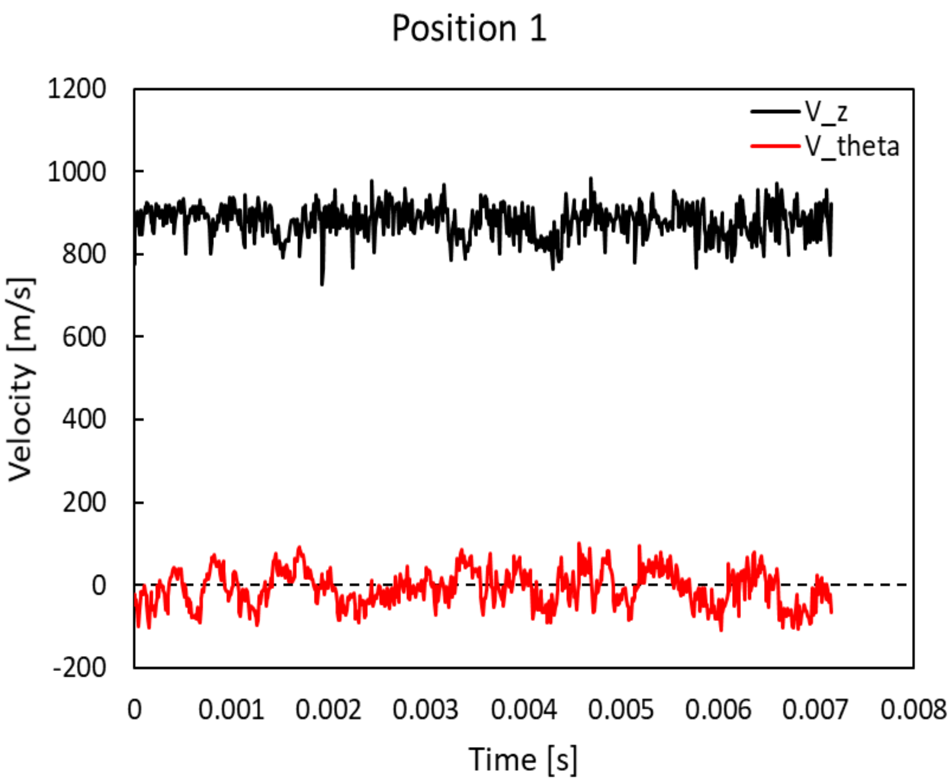
Engineering Scale 13.4” RDE Testing at Purdue University

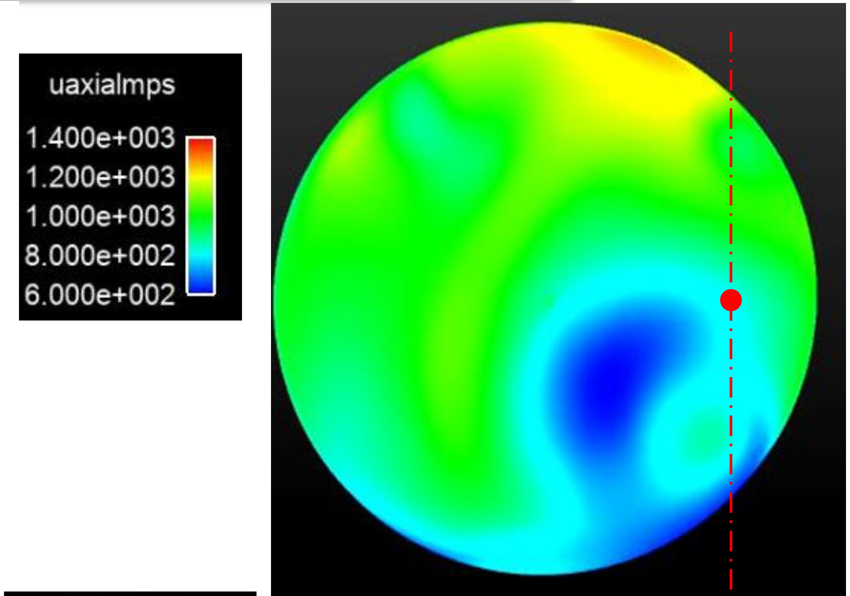
- Latest tests utilize 100kHz PIV to obtain 2-D velocity vector map of exhaust with supersonic shockwaves
- Demonstrated strong detonation with a ver
- Demonstrated strong detonation at low equ

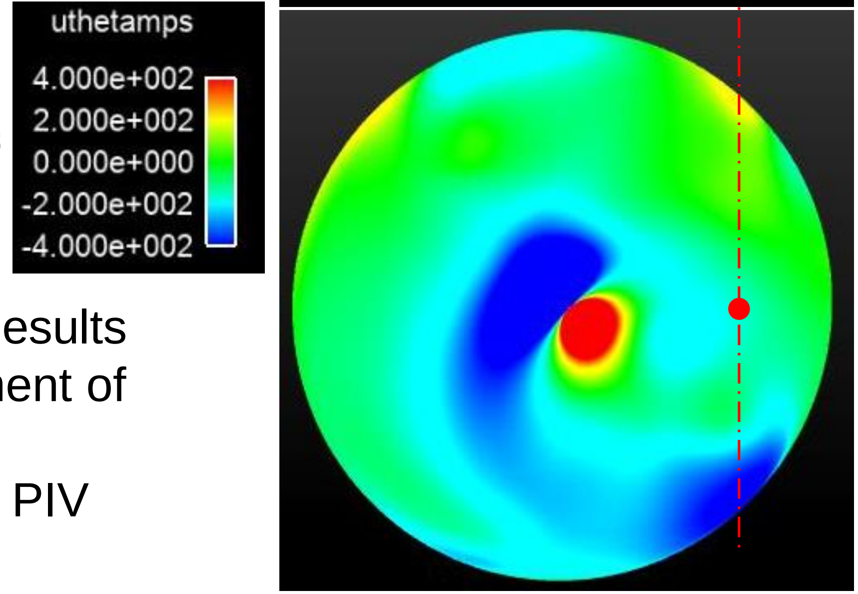


Comparison to Purdue PIV Results: Diffuser

Shark Fin with Diffuser (Config 11)

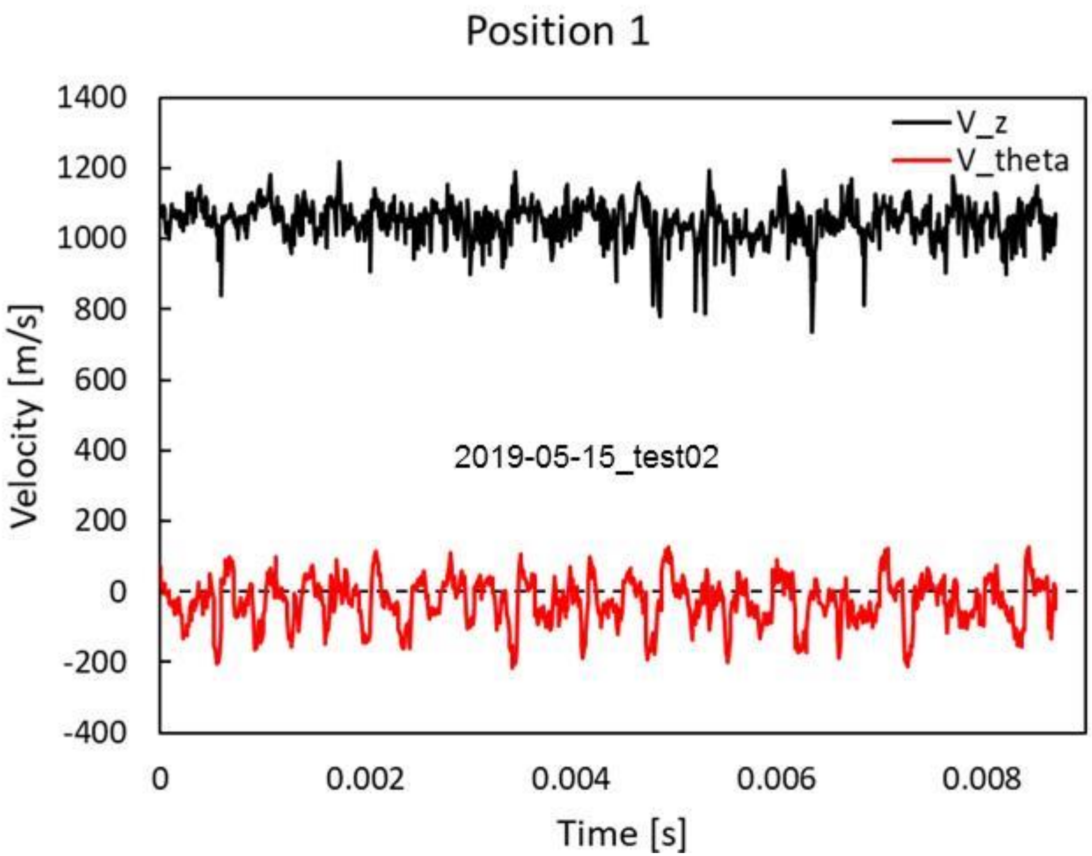


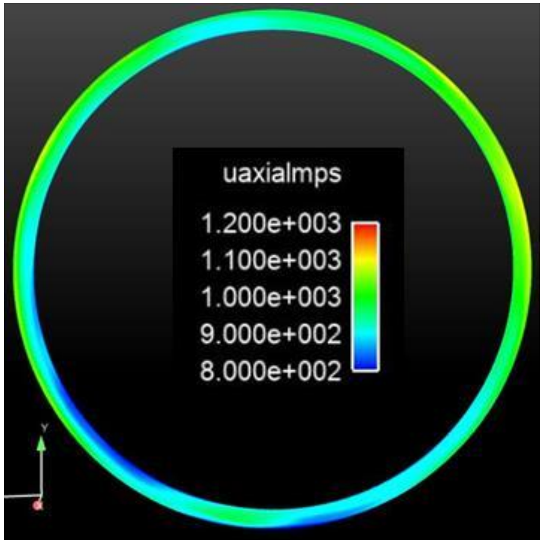


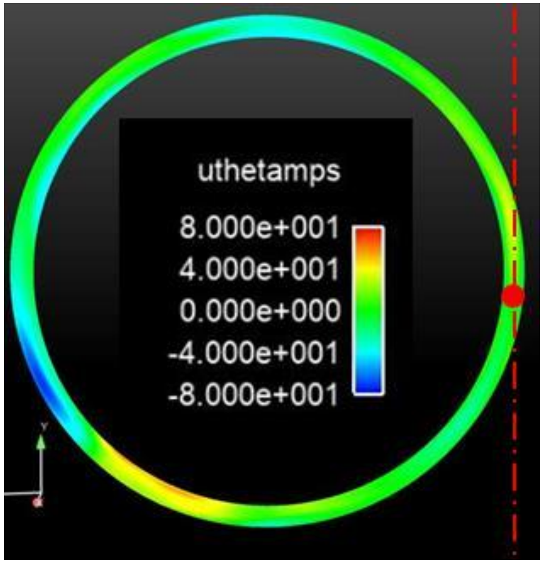


- V_{theta} at Midline Similar to Aperiodic Test Results
- Centerline Vortex Seen in CFD; Development of Secondary Frequencies
- CFD Axial Velocity Appears Within 10% of PIV

Comparison to Purdue PIV Results: Annulus Exit
Config 13 with Back Pressure Nozzle

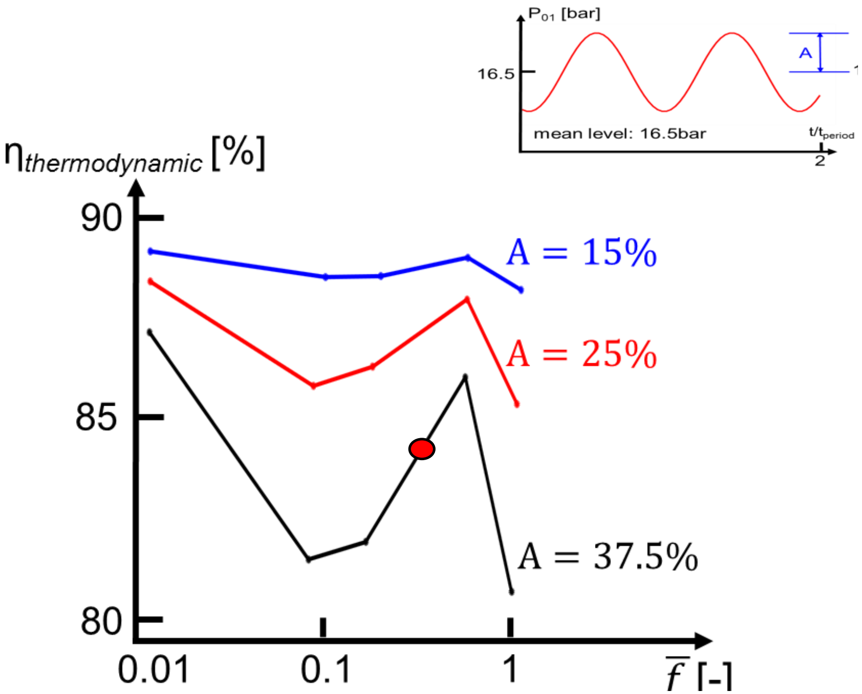




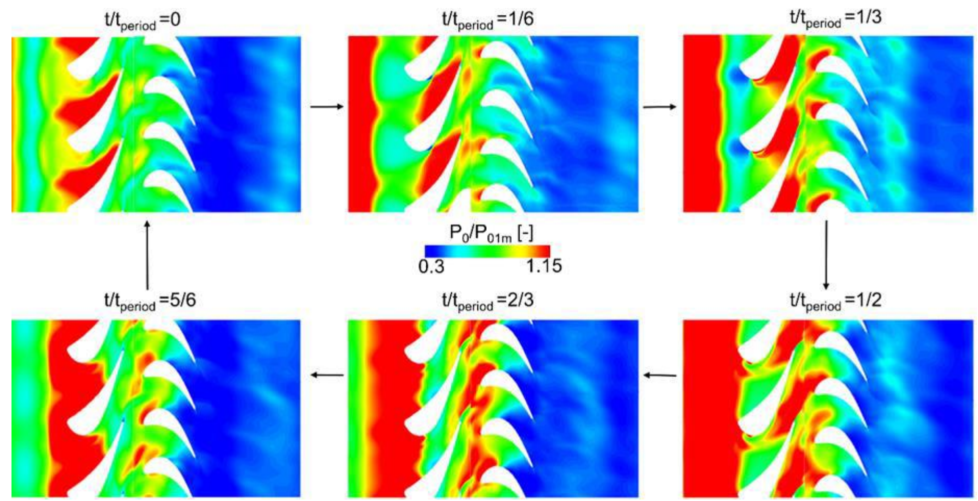


- Good Agreement with Radial Midplane
- Reasons for Disturbances from Self-Similar Cycles Seen in Off Center CFD

Turbine Design Optimized for RDE Unsteady Flow
Purdue: Dr. Guillermo Paniagua

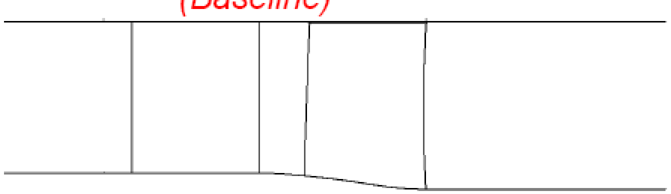


Amplitude

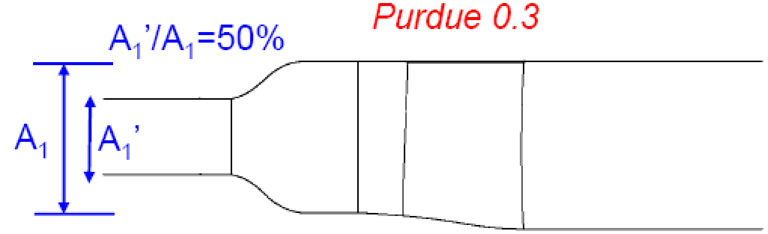


1st rotor and stator benefit from blade shape optimization via unsteady CFD

TATEF (Baseline)



Purdue 0.3

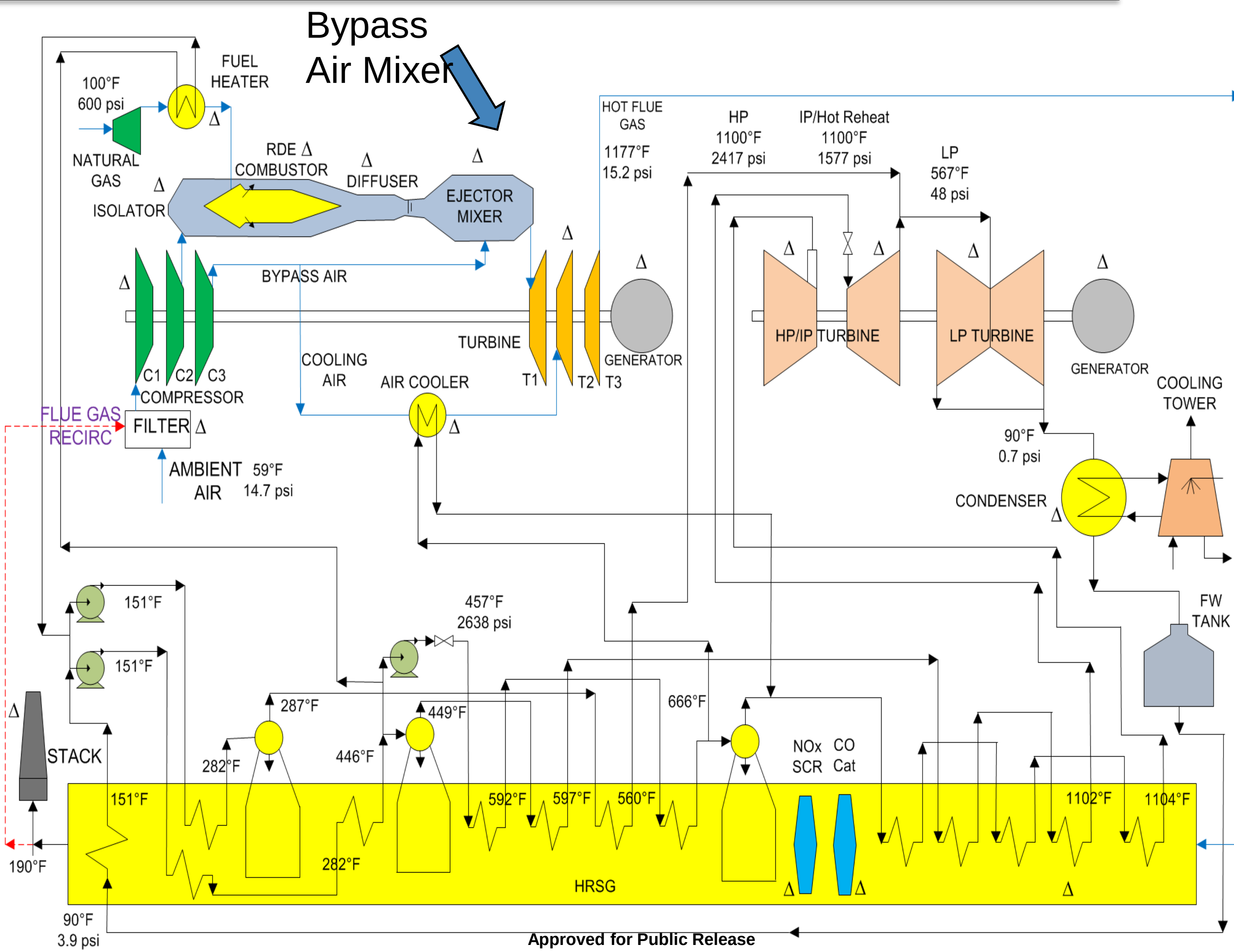


- Un-modified blade profiles resulted in unacceptable performance loss (64.9% efficiency)
- Modified blade has 89% Efficiency with 15% P Oscillations from Diffuser

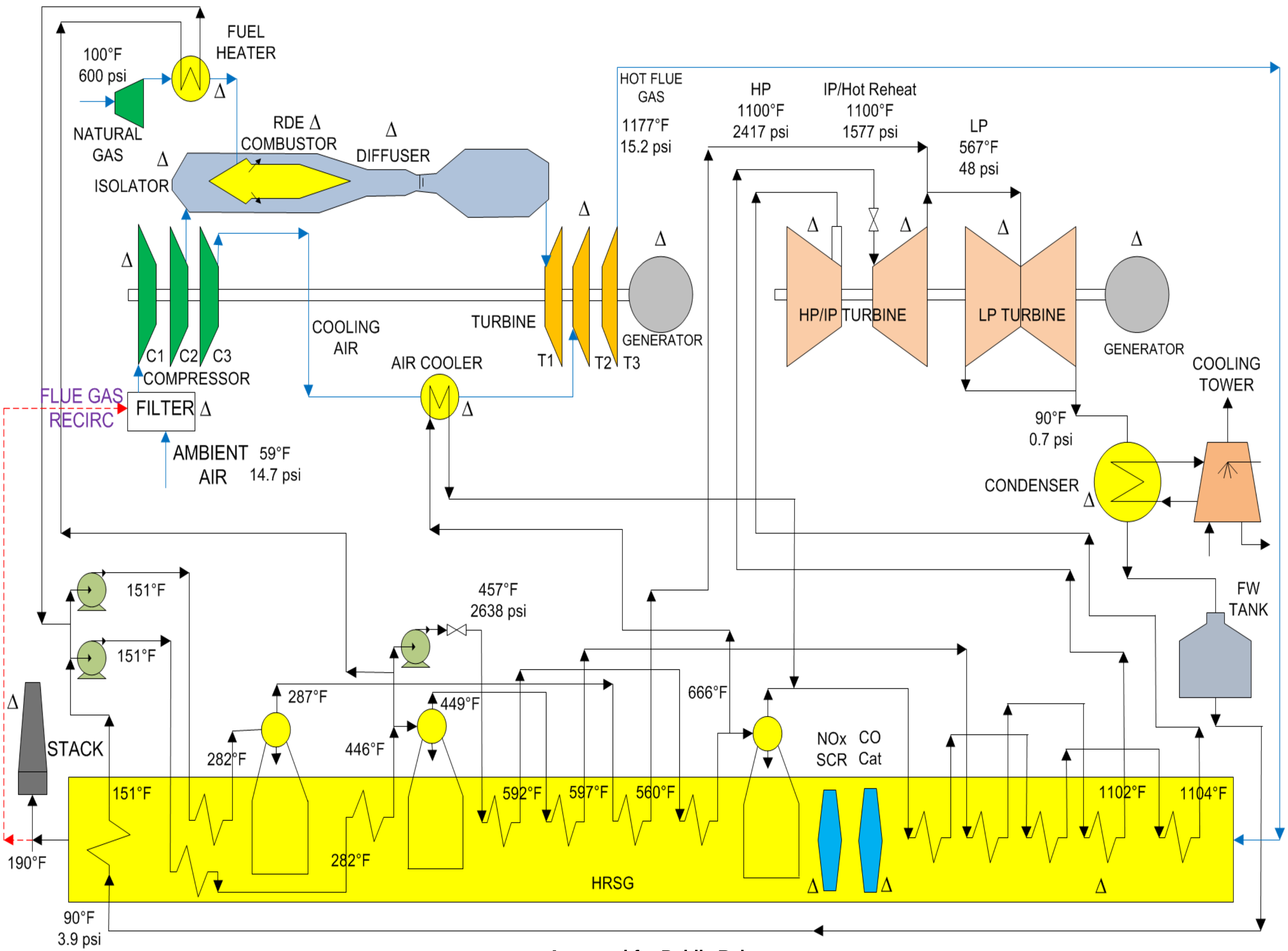
Approach to NGCC Plant Performance Modeling

1. Develop a power plant mass and energy balance system model integrating an RDE with a gas turbine-based power generation system
2. Define the RDE and the interaction of the RDE with the pieces of the gas turbine system through component models encapsulating the operation of these components with real, as opposed to ideal, performance in succinct fashion
3. Determine the efficiencies defined in these component models through Hotfire Tests and unsteady, multidimensional, computational fluid dynamics (CFD)
4. Validate the CFD models feeding this system model with in-stream-probe pressure and flow angle measurements of an RDE operating under conditions traceable to gas turbine operation
5. Employ this system model based on realistic performance for product system trades to define the path to an advanced combustion turbine in a combined cycle application capable of meeting or exceeding 65% combined cycle efficiency.

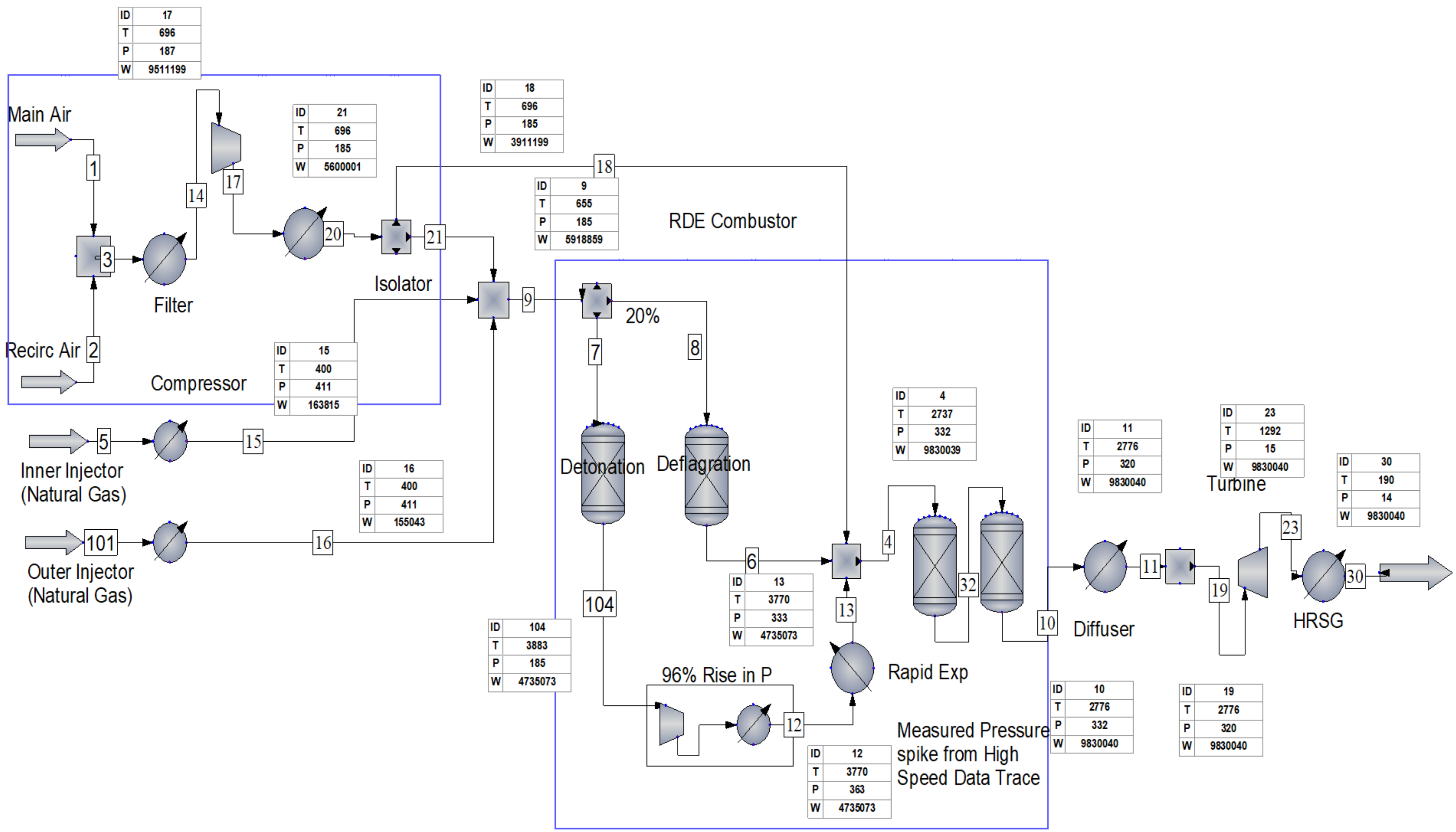
RDE NGCC Plant Schematic: Compressor for Bypass Air and Mixer



RDE NGCC Plant Schematic: Tailored Flow (No bypass Flow/mixer)



Gas Turbine Cycle Simulation: Tailored Flow Case



Plant Performance: Tailored Flow Case

Plant Output			
	J (3a) - DOE	J - RDE	
Gas Turbine Power	689,832	772,069	kWe
Compressor Power(-)	-	-	kWe
Steam Turbine Power	314,517	289,377	kWe
Total	1,004,349	1,061,446	kWe
Auxiliary Loads			
Condensate Pumps	-	-	kWe
BFW Pumps	6,725	6,187.46	kWe
Circ Water Pumps	2,941	2,705.92	kWe
Ground Water Pumps	300	276.02	kWe
Cooling Tower Fans	2,180	2,005.75	kWe
SCR	10	15.00	kWe
GT Auxiliaries	1,097	1,009.31	kWe
ST Auxiliaries	672	618.29	kWe
Misc BOP	3,434	3,159.51	kWe
Transformer Losses	5,022	4,620.58	kWe
Total	22,381	20,598	

Plant Performance			
	J (3a) - DOE	J - RDE	
Net Plant Power	**981,968**	**1,040,848**	**kWe**
Plant Capacity Factor	85	85	
Net Plant Efficiency (HHV)	56.5%	59.9%	
Net Plant Efficiency (LH	**62.6%**	**66.4%**	
Net Plant Heat Rate (HHV	6,036	5,694	Btu/kWh
Net Plant Heat Rate (LHV)	5,448	5,140	Btu/kWh
Nat Gas Feed Flow	263,520	263,520	lb/hr
Nat Gas HHV	22,491	22,491	Btu/lb
Nat Gas LHV	20,301	20,301	Btu/lb
Thermal Input HHV	1,736,982	1,736,982	kWt
Thermal Input LHV	1,567,848	1,567,848	kWt
Condenser Duty	1,530	1,408	MMBtu/h
Raw Water Withdrawal	3,309	3,045	gpm
Raw Water Consumption	2,744	2,525	gpm

Derived from measured test data

RDE Based GT NGCC offers higher efficiency, exceeding DOE goal 65%

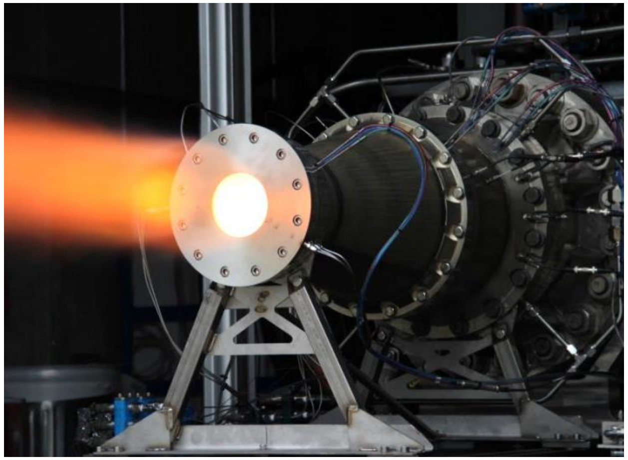
RDC-Powered NGCC Plant Analysis Summary

- Mass & Energy Balance was successfully modelled using combination of ChemCAD 7.1.4.10142
- For the same NG and Air flow, Capital Cost ($/kW) was estimated using QGESS and found to be 8.5% higher, Variable Opex was 24% higher while Fixed Opex was 5.5% Lower than commercial J Class turbine.
- LCOE was estimated using QGESS and found to be 2.5% lower than commercial J Class turbine.
- CO2 emitted was found to be lower (on lb/MWe basis) by 5.66%
- Steam bottoming cycle, although less efficient than RDE cycle, Reduces Sensitivity to Component inefficiencies
- Net plant efficiency of goal RDE plant is 66.4% (LHV) as compared to 62.6% baseline commercial J class offering from MHI

Program Summary

- **All RDE test hardware and test operations completed, providing improved design knowledge for large scale NG/Air RDE test at Purdue**
- **Four facilities built with significant capability in RDE hot fire testing and diagnostics**
- **Many RDE hardware testbeds up to 13.4”; modular, available with advanced instrumentation and diagnostic capability**
- **State of the art PIV diagnostics improved throughout the program**
    - **Provided detailed flow characteristics of exhaust flow**
    - **Improved analysis and design of diffuser to reduce pressure losses**
- **Over 700 tests conducted**
- **Measured static and dynamic pressure and CFD provided basis for PGC analysis**
    - **Diffuser recovers dynamic pressure from unsteady flow**
    - **Isolator/Injector is largest contributor of pressure losses**
- **Tests with low loss injector and tailored flow indicate potential for significant plant efficiency improvement**
- **CFD updates for RDE analysis, post test mixing improvement indicates 33% pressure gain**
- **NGCC plant efficiency > 66% with PGC w/ RDE test based inputs**
    - **Cost of Electricity lower than case 3A [J-Class Mitsubishi turbine NGCC, 2011]**

Image: 13.4” RDE w/ diffuser

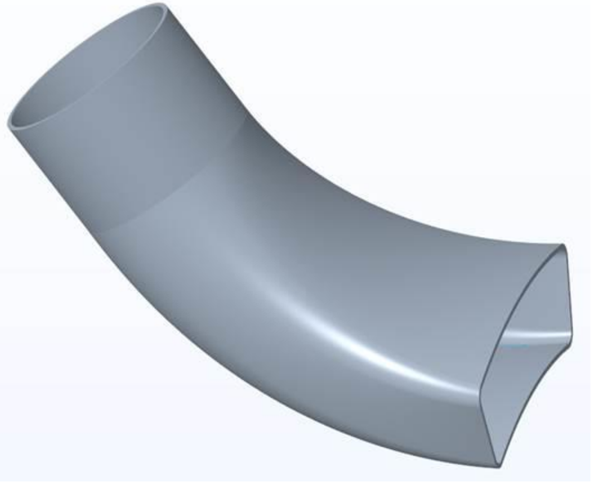


Recommendations / Future Work

- Further demonstrate low loss RDE operation with improved fuel injection at Engineering Scale
  - Greater pressure gain with higher magnitude pulses
  - Enhanced instrumentation

Image: Exhaust plume of 13.4” RDE w/ NG+air

- Explore limits of purposeful injector flow tailoring on detonation combustion
  - Significant impact on plant efficiency
  - Demonstrate target exit temperature



- Investigate integration with application geometry transition ducts
  - Next generation exhaust diffuser