Overview of Rotating Detonation Combustion Research at the National Energy Technology Laboratory

Solutions for Today | Options for Tomorrow

NATIONAL ENERGY TECHNOLOGY LABORATORY

University Turbine Systems Research
2022 Project Review Meeting
Sept 27-29, 2022
San Diego State University
San Diego, CA

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Research and Innovation Center
National Energy Technology Laboratory

U.S. DEPARTMENT OF ENERGY

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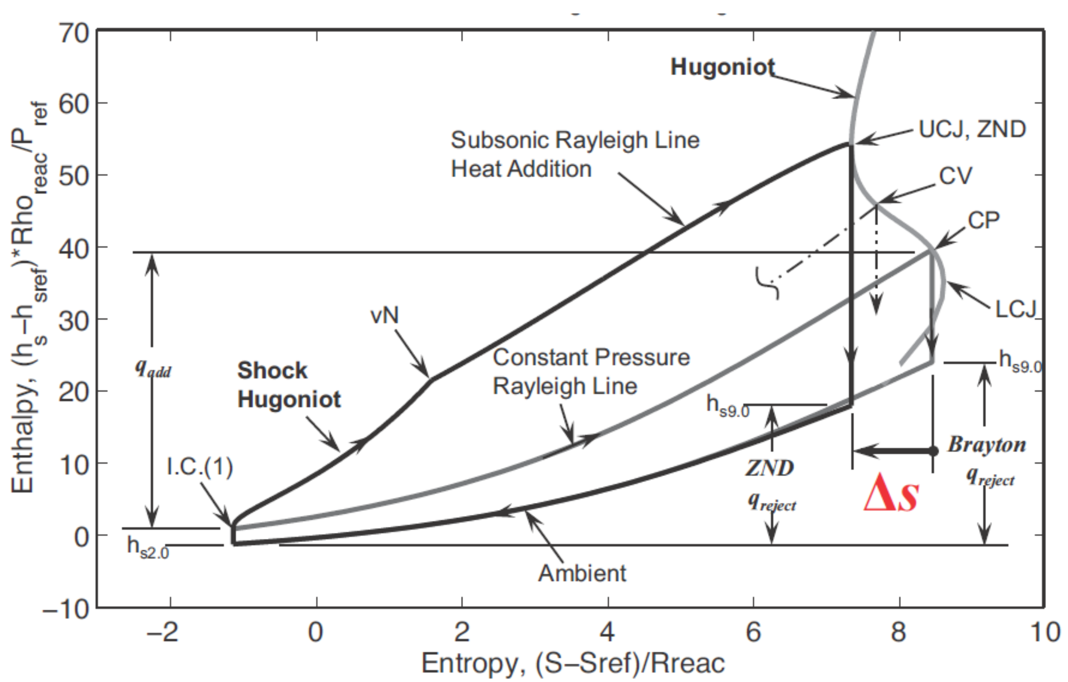
Outline

- Introduction / Motivation
- DOE Program Objectives / Activities
- NETL-RIC Project Objectives
- Results / Analysis
- Summary

Potential Cycle Benefits from PGC

- **Constant volume combustion offers greater thermodynamic availability than constant pressure combustion**
  - 4.9% increase in GT Efficiency (LHV)
  - 1.8% increase in Net Plant Efficiency (NGCC with H-Class RDE-GT Hybrid)
  - Alternate and additive pathway to efficiency improvement
    - Combine greater work availability to conventional approach to efficiency gains through higher turbine inlet temperatures.



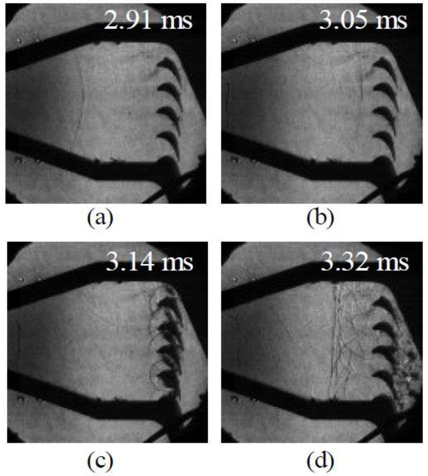
H-S diagram comparing constant pressure combustion (Brayton) cycle to near-constant volume combustion (Humphrey) cycle.

- **Hydrogen utilization**

- **Offers potential for distributed power and Alternative Energy integration**

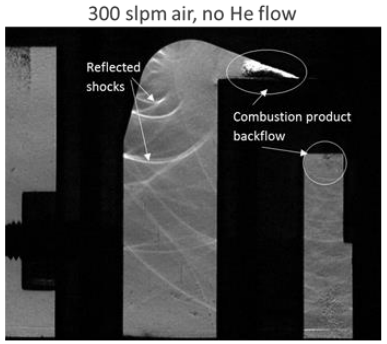
DOE PGC Program Objectives

- **Gas Turbine Integration**
  - Improved cycle efficiency
    - PGC is inherently unsteady
      - Unsteady flow in the combustor can impact both the compressor and turbine performance.
        - Mechanical concerns
    - Fuel-oxidizer mixing
    - High turbine inlet Mach numbers are not compatible with industrial turbines.
    - Properly characterize cycle benefits
  - Hydrogen-Air Combustion
    - Combustion stability
    - NOx formation pathways
  - High heat flux can pose a challenge for component cooling
    - Cooling air injector at higher pressure??
- **Alternative power cycles**



Sequence of still images showing passage of a strong shock through the 2D cascade test rig.

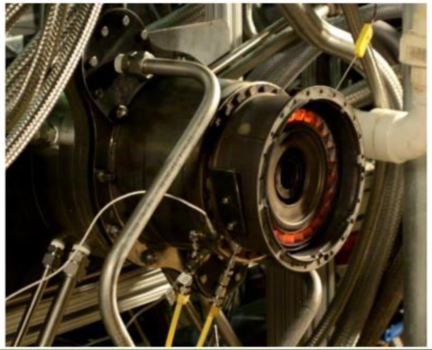
Rasheed et al. (2004), https://doi.org/10.2514/6.2004-1207



NETL Lab-Scale RDE Inlet Sector Rig

Upstream propagation of shock waves in a RDE radial injector

Bedick et al. (2017), https://doi.org/10.2514/6.2017-0785



RDE coupled to T63 Turbine at AFRL
Naples et al., AIAA 2017-1747

University of Michigan

PI: Dr. Mirko Gamba (Dr. Venkat Raman [Co-PI])

- **Fuel Injection Dynamics and Composition Effects on Rotating Detonation Engine Performance (2017 – 2021)**
  - Detonation wave – injector dynamics, mixing
- **Pressure Gain, Stability, and Operability of Methane/Syngas Based RDEs Under Steady and Transient Conditions (2019 – 2022)**
  - Quantitative description of the loss mechanisms
  - Characterize metrics for evaluating performance gains
- **Machine learning based approach to combustion modeling and GPU-accelerated solvers (DOE Office of Advanced Scientific Computing Research's Leadership Computing Challenge – ORNL Summit Supercomputer)**

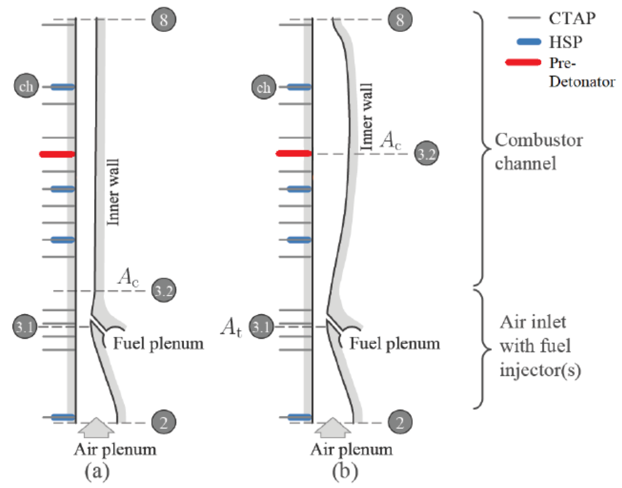


Fig. 1 Schematic diagram of (a) narrow and (b) wide channel RDC flow-paths. The two configurations differ only by the inner wall contour.

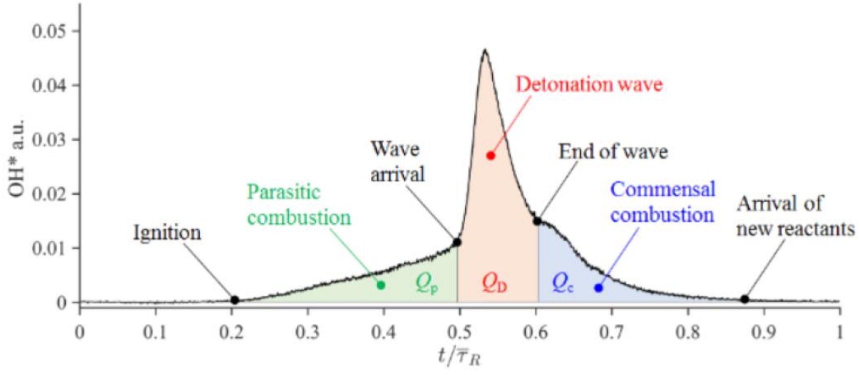
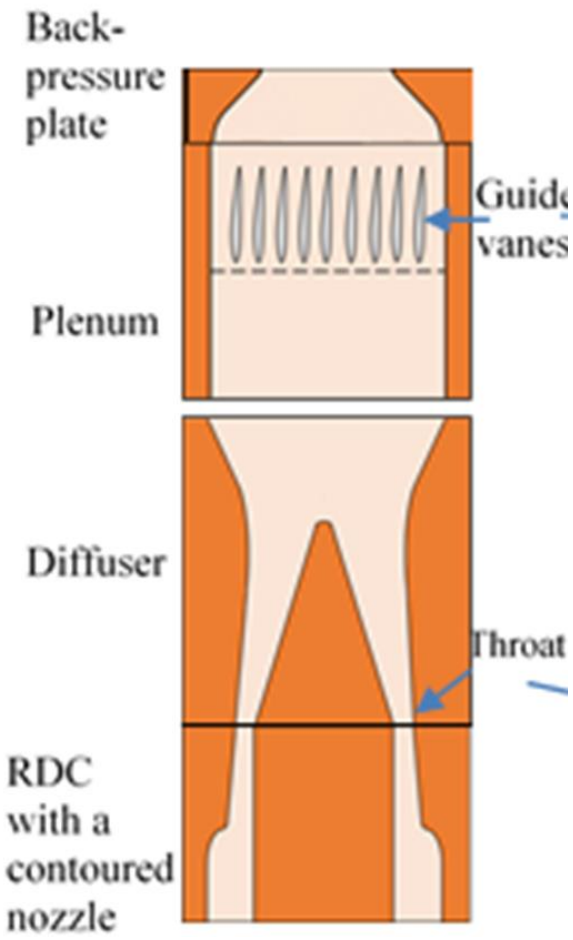


Fig. 3 Estimation of average heat release during a RDE cycle using OH emissions.[7]

University of Alabama

PI: Dr. Ajay Agrawal (Dr. Joseph Meadows [Co-PI] – Virginia Tech)

- **A Robust Methodology To Integrate Rotating Detonation Combustor With Gas Turbines To Maximize Pressure Gain (2021 – 2024)**
  - Optimized RDC-Diffuser design for improved turbine integration
    - RDC Channel area profiling to improve detonation stability and performance
  - Quantify the impact of loss mechanisms in the combustion process associated with non-ideal mixing, mixed mode combustion (deflagration/detonation), and wave mode/numbers in the RDC



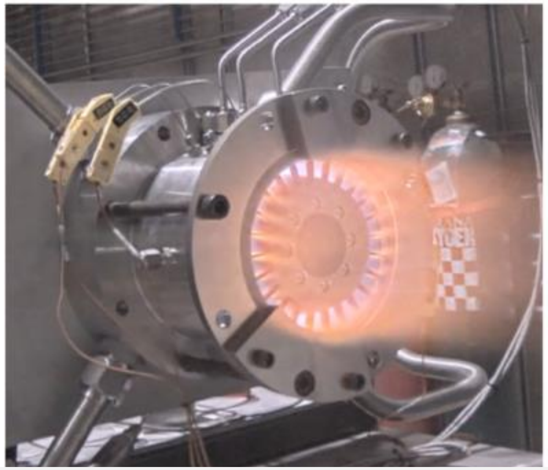
Purdue University

PI: Dr. Guillermo Paniagua, James Braun, Terry Meyer, Pinaki Pal, Carson Slabaugh

- **Physics-Based Integration of H2-Air Rotating Detonation into Gas Turbine Power Plant (2021 - 2024)**
- **Objectives**
  - improve turbine overall work extraction with a diffuser-turbine efficiency of 90%
  - Air dilution of 100% or less
  - Minimize heat fluxes
  - Ensure adequate damping to the rotating blades

Scope of Work

- Identify the scaling parameters that emulate the RDC outlet conditions to enable TRL2/TRL3 testing
- Design and assessment of an optimized axisymmetric diffuser under pulsating flow
- Optimization and assessment of an industrial turbine vane under pulsating differ exit flow



Integration of diffuser-vane in optical accessible RDC

GE Research

PI: Dr. Keith McManus and Dr. Kapil Singh

Demonstration of a Gas Turbine-Scale RDC Integrated with Compressor and Turbine Components at 7FA Cycle Conditions (2022 – 2026)

Project Team

GE Research

Deep expertise:
- RDC and gas turbine design
- Gas turbine testing
- Compressor/diffuser aero
- Turbine aero
- Cooling design, heat transfer

Computational Combustion and Aero

University of Michigan

Prof. Raman

Measurements and Diagnostics

UCF

Prof. Vasu

Georgia Tech

Prof. Steinberg

NC State University

Prof. Narayanaswamy

Project Deliverables

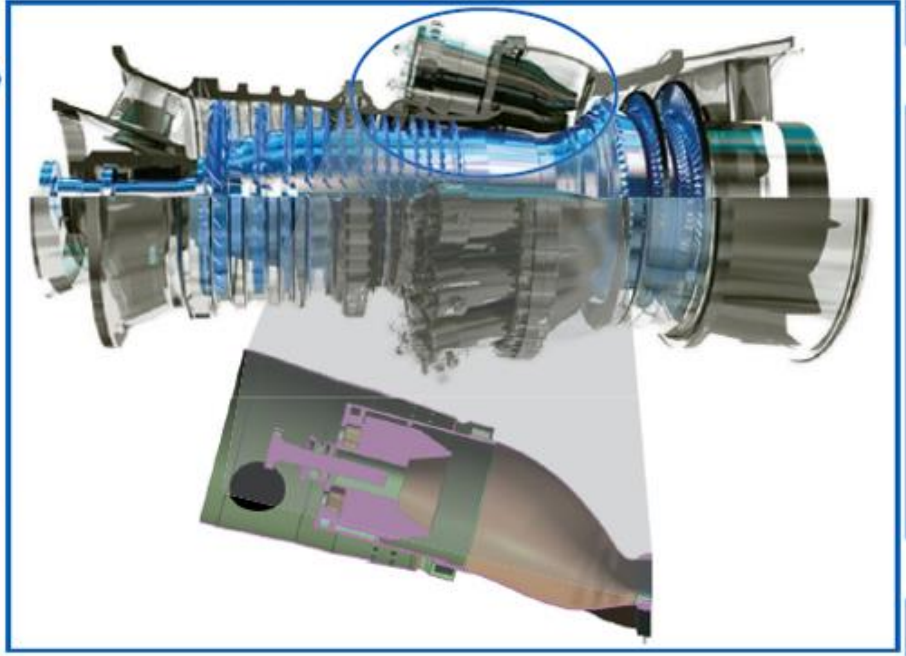
- Low-loss RDC design for turbine integration
- Experimental demos of compressor and turbine integration
- Turbine and compressor component performance estimates in integrated system from detailed test and measurement
- RDC-integrated GT performance estimates

Relevant Prior Work

- Air-cooled RDC demonstration
- RDC operation on natural gas at elevated T,P
- Preliminary gas turbine integration design
- RDC performance estimates
- USAF RDC Program

An 48-month, $8.75M project to develop and demonstrate rotating detonation combustion (RDC) technology in an integrated gas turbine system.

Project Objective(s): Develop low-loss rotating detonation combustor, integrate with upstream and downstream turbomachinery components and verify overall systems performance at F-class turbine conditions.



Technical Approach
- Design air-cooled RDC
- Test with Nat-gas H2 mixtures
- Integrate with compressor and turbine
- Test integrated system
- Verify performance based on high-fidelity data

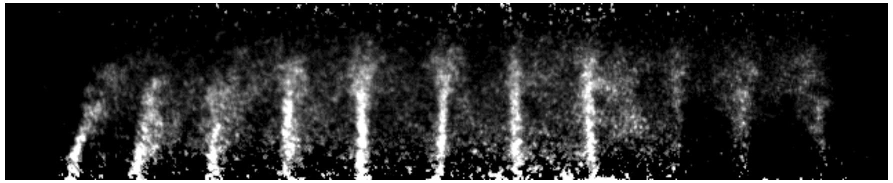
Technical Challenges
- RDC operation over large P,T range
- Low-loss RDC inlet design
- Fuel flexible operation
- Unsteady flow effects on compressor and turbine performance

NETL-RIC RDE Research Objectives

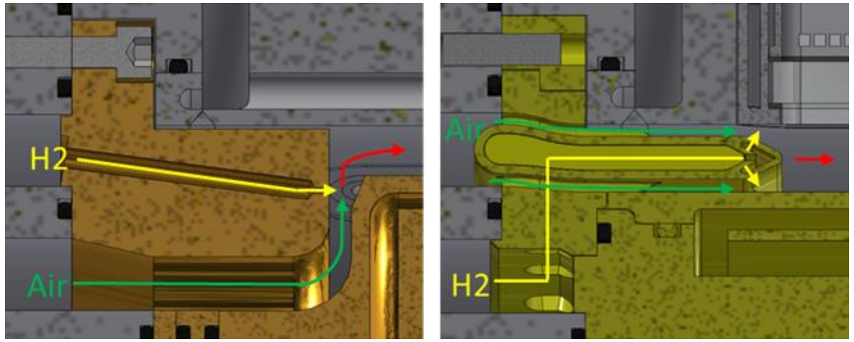
- **Improve fundamental understanding stable continuous wave detonation**
  - Wave directionality, bifurcation, translation speed (~CJ)
  - Det / shock wave influence on operational parameters (i.e fuel injection/mixing, combustion stability)

- **Maximize pressure gain / turbine work availability and reduce emissions**
  - Inlet / exhaust transition configuration for turbine integration
  - Reduce parasitic losses from deflagration
  - Control NOx emissions

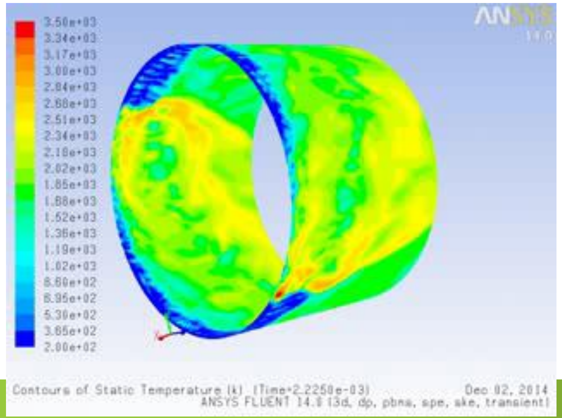
- **Improve modeling capabilities**
  - Simultaneous detonation and deflagration (turbulent combustion model)



NETL Characterization of Injector Response using Acetone PLIF



Varying the Fuel / Oxidizer injection schemes and sizes



Temperature contours from simulation of RDE operating on H2-Air (NETL).

Argonne National Laboratory

PI: Dr. Pinaki Pal (Xu, Ameen, Som, Ferguson, Strakey)

- **Tasks**
  - Analysis of Injector Design Effects on RDE Parasitic Combustion
  - Investigation of the Impact of RDE Ignition Mechanism on Detonation Wave Behavior

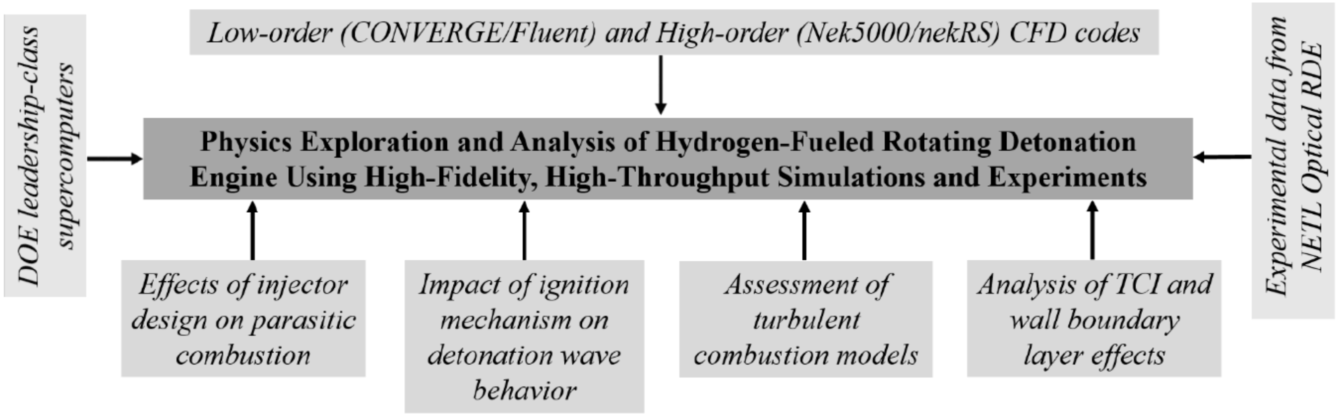


Figure 1: Overall proposed joint Argonne-NETL research effort on hydrogen-fueled RDE.

  - Exploring Turbulent Combustion Models for Predictive and Computationally-efficient RDE CFD Simulations
    - Argonne will test a CEMA-based dynamic adaptive combustion model [14] which assigns either FRC or unsteady flamelet progress variable (UFPV) or inert mixing model to the local mixture depending on the local combustion regime identified by CEMA.
  - High-order Nek5000 CFD Framework for Scale-Resolving Simulations of RDEs and analysis of TCI and wall boundary layer effects

Task 2: Pressure Gain Combustion

Project Timeline Overview

NATIONAL ENERGY TECHNOLOGY LABORATORY

2021 Budget	Research Activities	2021			2022				2023			
		Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
$653k	Task 2: Pressure Gain Combustion											

Milestones

1. Develop advanced diagnostics utilizing computer vision and machine learning (07/31/2021).
2. The impact of long-duration versus short-duration testing on experimental studies of RDEs. (5/31/2022)
3. Complete / Document installation of axial air injection scheme and exhaust diffuser in water-cooled RDE. (05/31/2022)
4. Quantify heat flux in the high-pressure, water-cooled RDE. (08/30/2022)
5. Experimental and computational characterization of several advanced inlet designs using a combination of experimental studies and computational modeling (12/31/2022)
6. Exhaust flow with diffuser characterization in optical RDE (05/31/2023)
7. Develop experimental capabilities for exploration of RDCs with DPE cycles. (10/31/2023)

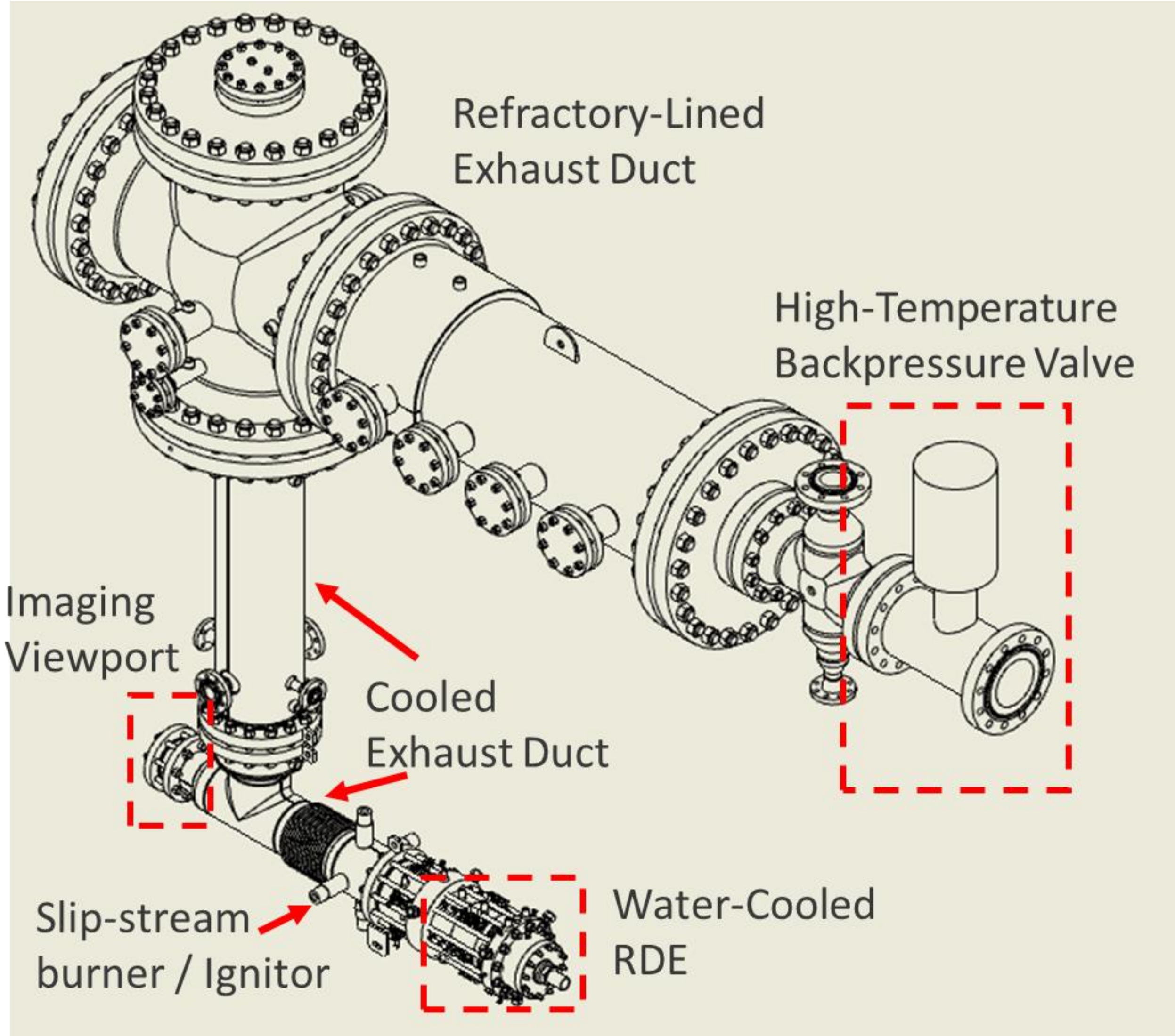
Go / No-Go

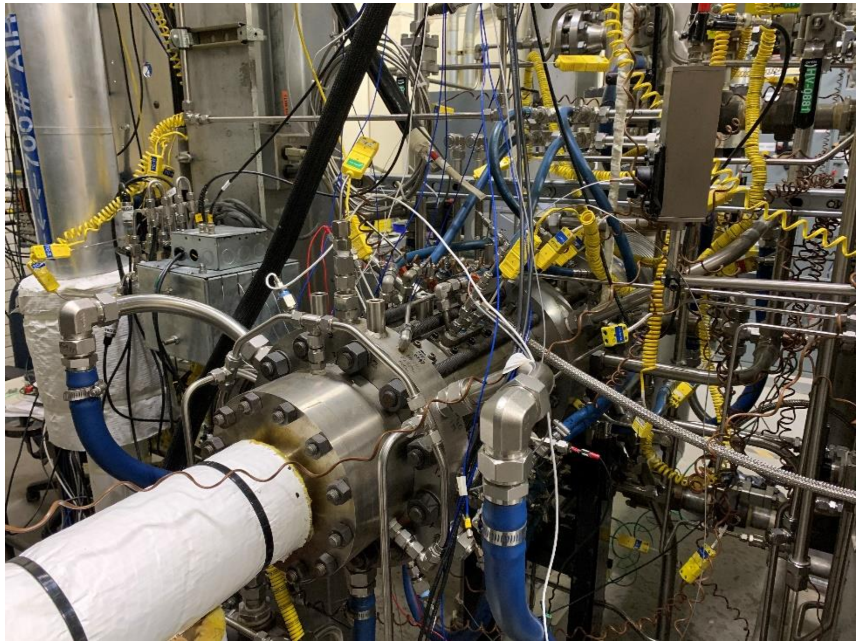
1. Installation of High-Temperature / Pressure Gas Cell (HTP Cell) in NETL-PIT Fundamental Combustion Laboratory (05/31/2022)
2. Complete installation of an atmospheric optical RDC in NETL-Morgantown (8/30/2022)
3. Develop seeding system for optical RDE to facilitate PIV and LDV. (12/31/2022)

Impact

Deliverables	Value Delivered
1. Documentation of axial air injection and thermally stable operation (05/31/2022) 2. Thin-file heat flux and water calorimetry to characterize heat transfer (08/30/2022) 3. NOx formation in detonation (10/31/2022) 4. Experimental / Computational characterization of low-loss injectors (12/31/2022)	• Increased NETL experimental capability • Provide insight to heat flux in RDE for research community. • Provide research community insight to develop/design process for low-loss injector geometry. • Characterize NOx formation mechanisms that occur in RDE compared to conventional deflagration.

Experimental Facility





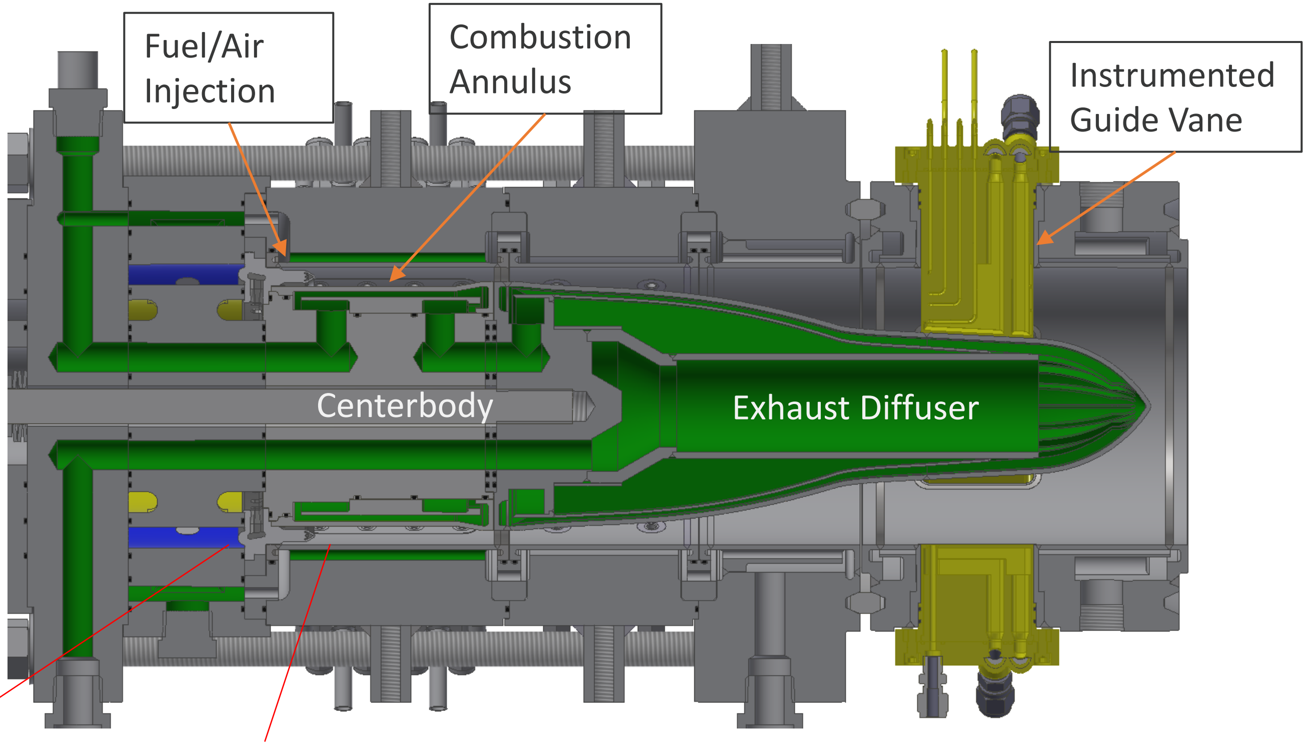
Operating Conditions

Fuels: H_2 and/or Natural Gas
air flow rate @ 600 K – 1 kg/sec
Max. shell T, P ≈ 477K, 16 Bar
Cooling: water @ 150 lpm, 11 Bar

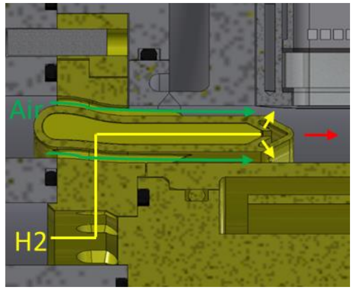
NETL Water-Cooled, High Pressure RDE

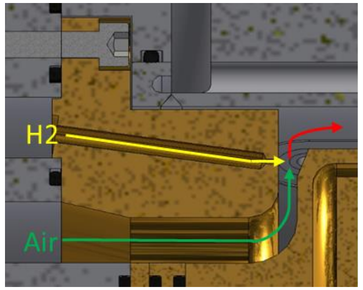
Injector / Combustor Geometry

Pintle Injector RDE Geometric Parameters			
Geometry		Geometry	
Comb-Injector Length (L1)-mm	133.5	Comb Length (L2)-mm	96.2
Comb Inner Diameter (Di_3.2)-mm	128.5		
Comb Outer Diameter (D0_3.2)-mm	148.8	Combustor Chamber Area (A3.2)-mm^2	4421
Comb Exit Inner Diameter (Di_8)-mm	133.6		
Comb Exit Outer Diameter (Do_8)-mm	148.8	Exit Nozzle Throat Area (A8)-mm^2	3371
Area Inlet Minimum Area (A3.1)-mm^2	1262	Fuel Inlet Minimum Area-mm^2	108.9
A3.1/A3.2	0.285	A8/A3.2	0.762



A3.1/A3.2	A8/A3.2
0.28	0.76



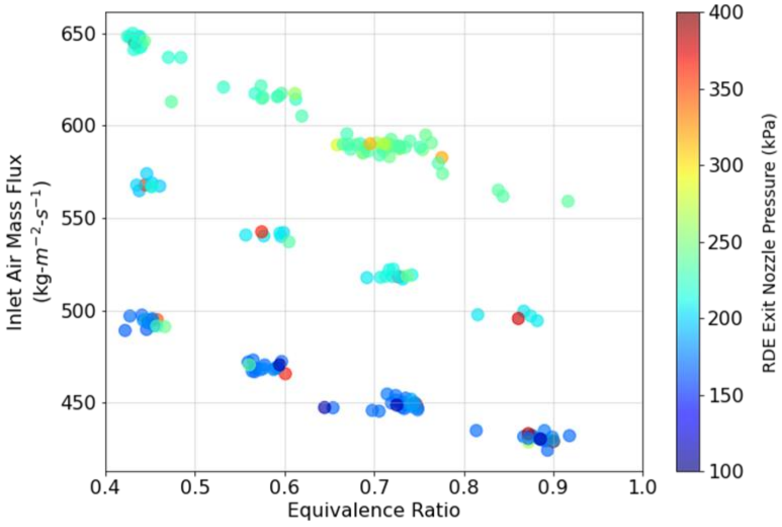


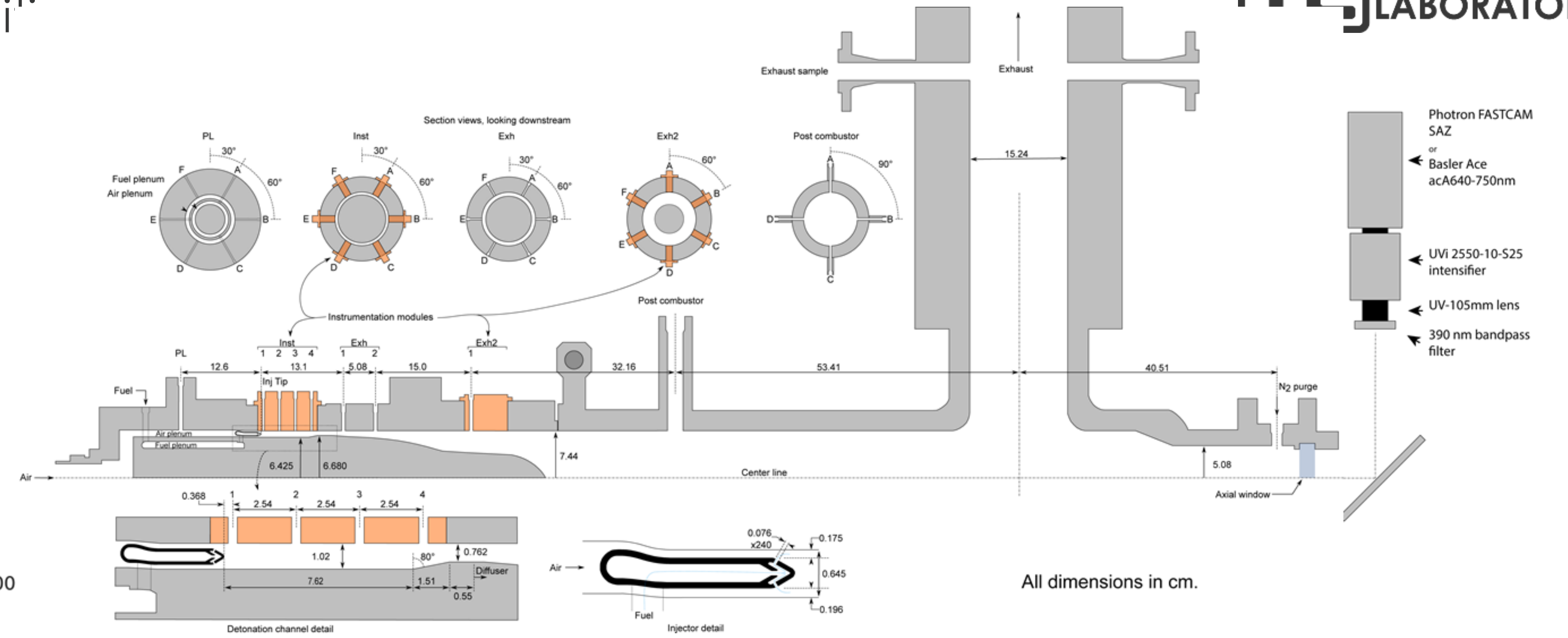
Air Injector Gap Size (mm)	A3.1/A3.2	A8/A3.2
0.56	0.06	1.0
0.79	0.09	
1.75	0.2	
2.8	0.32	

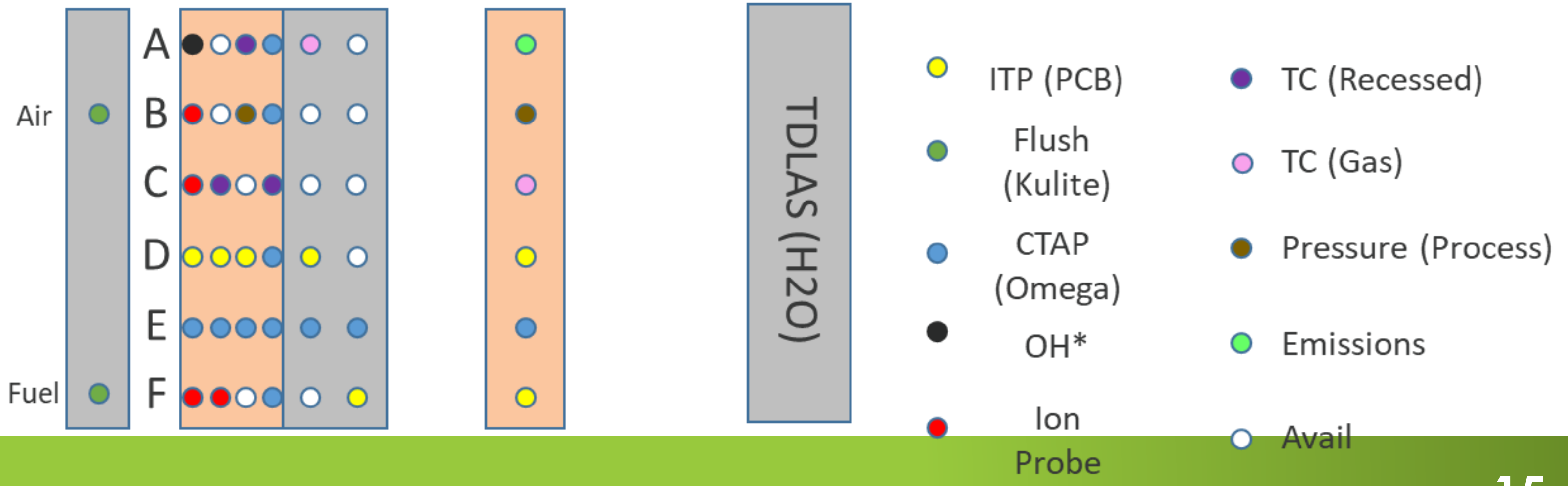
NETL Water-Cooled, High Pressure RDE

Instrumentation and Test Condi"

Air Mass Flux [kg m^{-2} s^{-1}]	phi	T_{air} [K]	P_{back} [kPa]
450	0.45, 0.6 0.75, 0.9	400, 475	101.3, 135 170, 240
500	0.45, 0.6 0.75, 0.9	400, 475	101.3, 135 170, 240
625	0.45, 0.6 0.75, 0.9	400, 475	101.3, 135 170, 240
650	0.45, 0.6 0.75, 0.9	400, 475	101.3, 135 170, 240

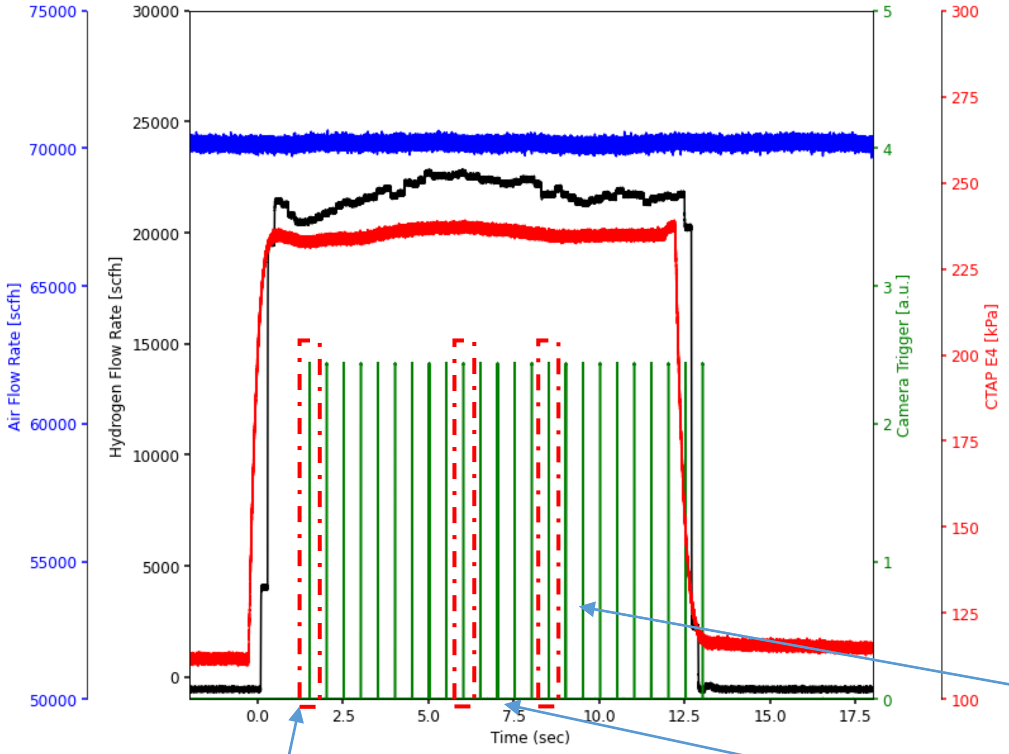


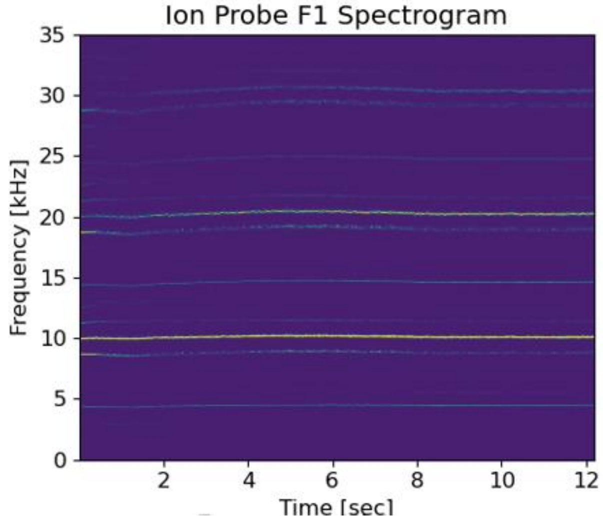


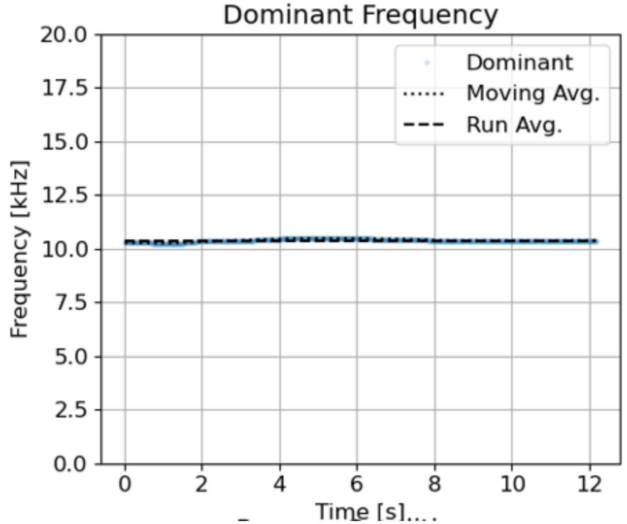


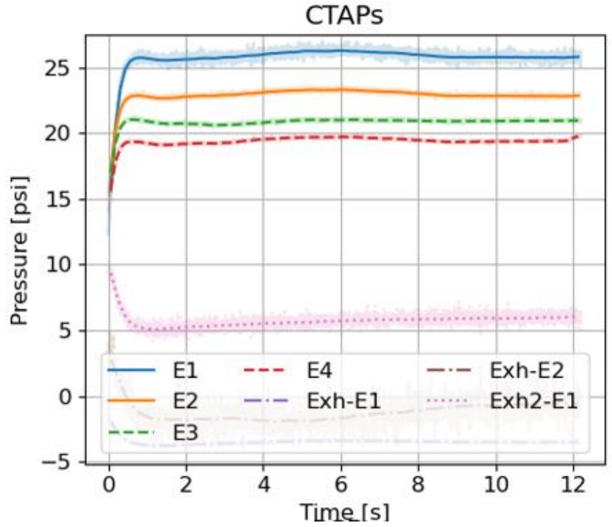
NETL Water-Cooled, High Pressure RDE

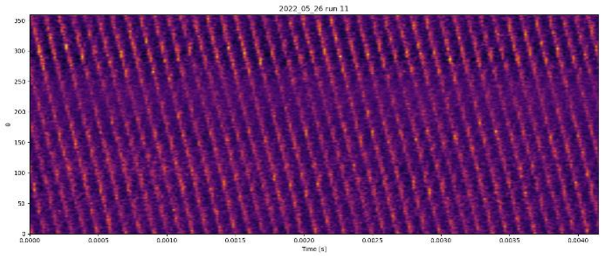
Typical Test Run and Results

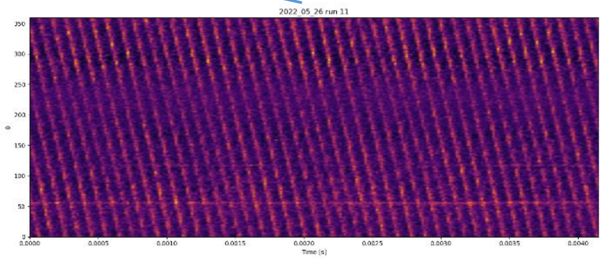


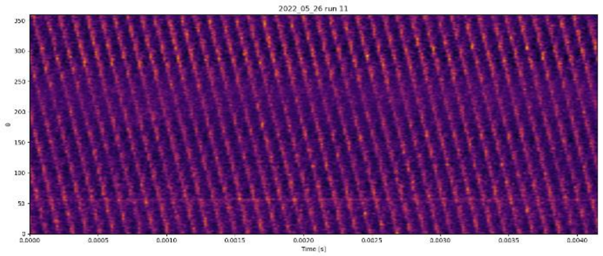






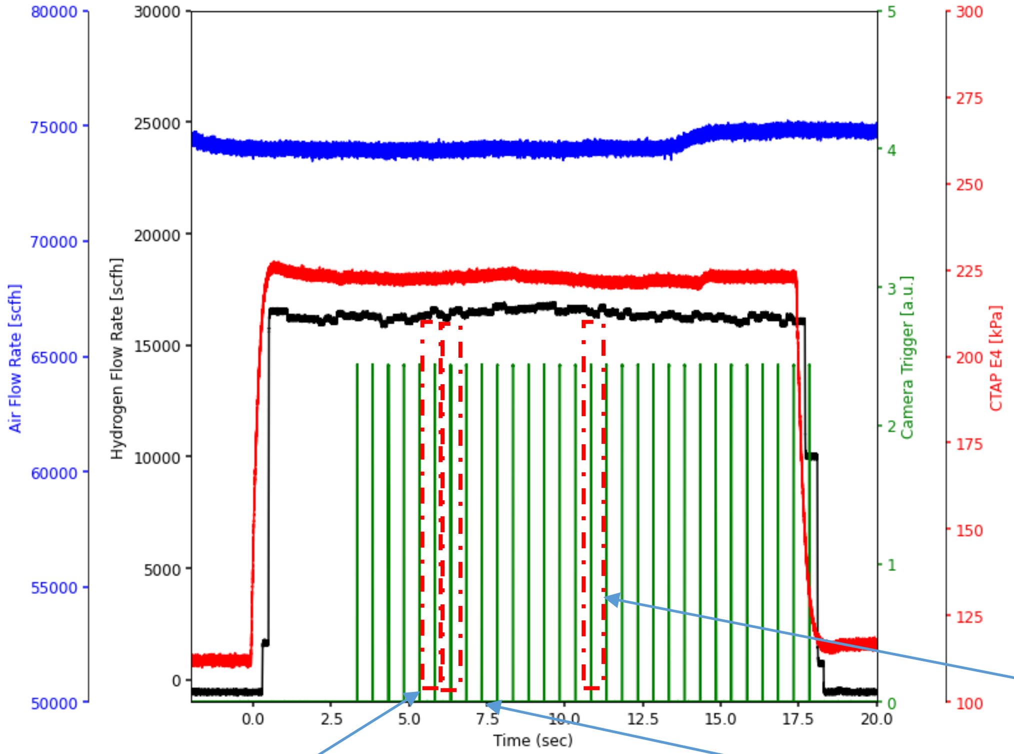


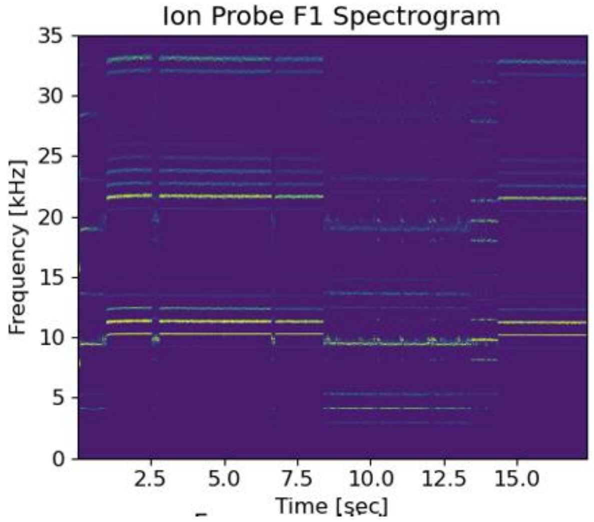


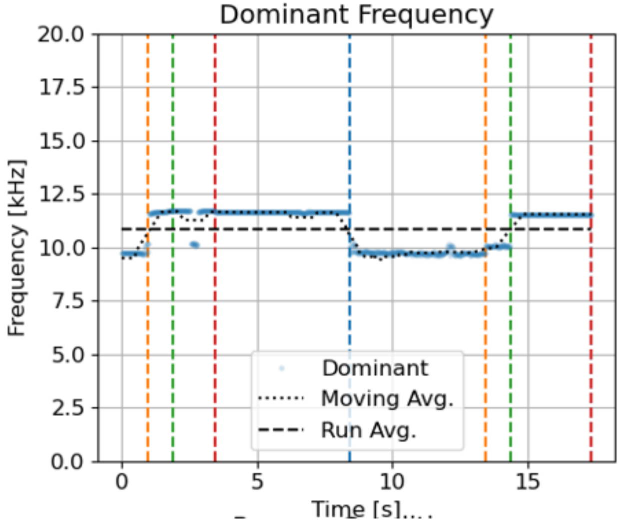


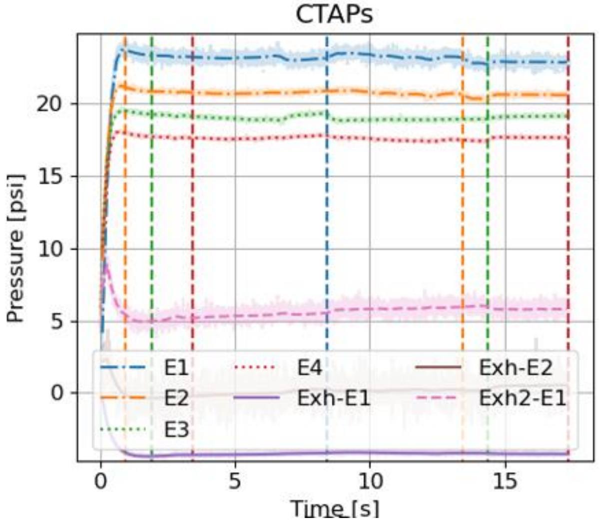
NETL Water-Cooled, High Pressure RDE

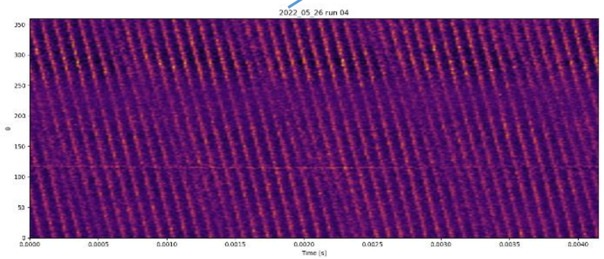
Modal Transitions

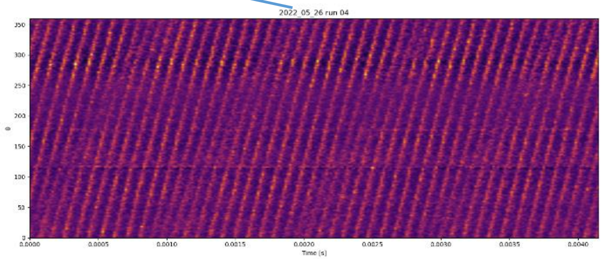


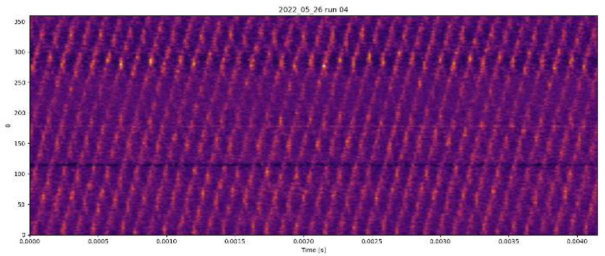












Real-time sensor for RDE Mode and Wave Speed

Machine Vision – Deep Learning Application

- Train convolutional neural network (CNN) on large pool of images with multiple modes
- Utilize CNN to predict wave mode (wave number and direction of rotation) from a single image
- Machine vision approach is being combined with conventional instrumentation (p’) to add instantaneous wave speed.

NETL images

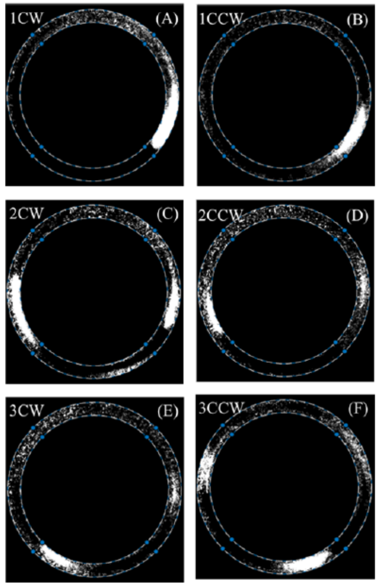


FIGURE 6: Downstream images of modes (A) 1CW, (B) 1CCW, (C) 2CW, (D) 2CCW, (E) 3CW and (F) 3CCW

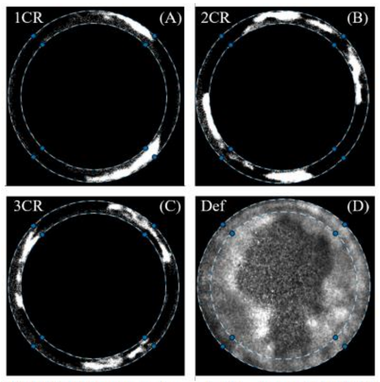


FIGURE 15: Downstream images of additional modes (A) 1CR, (B) 2CR, (C) 3CR, and (D) Def

Purdue images

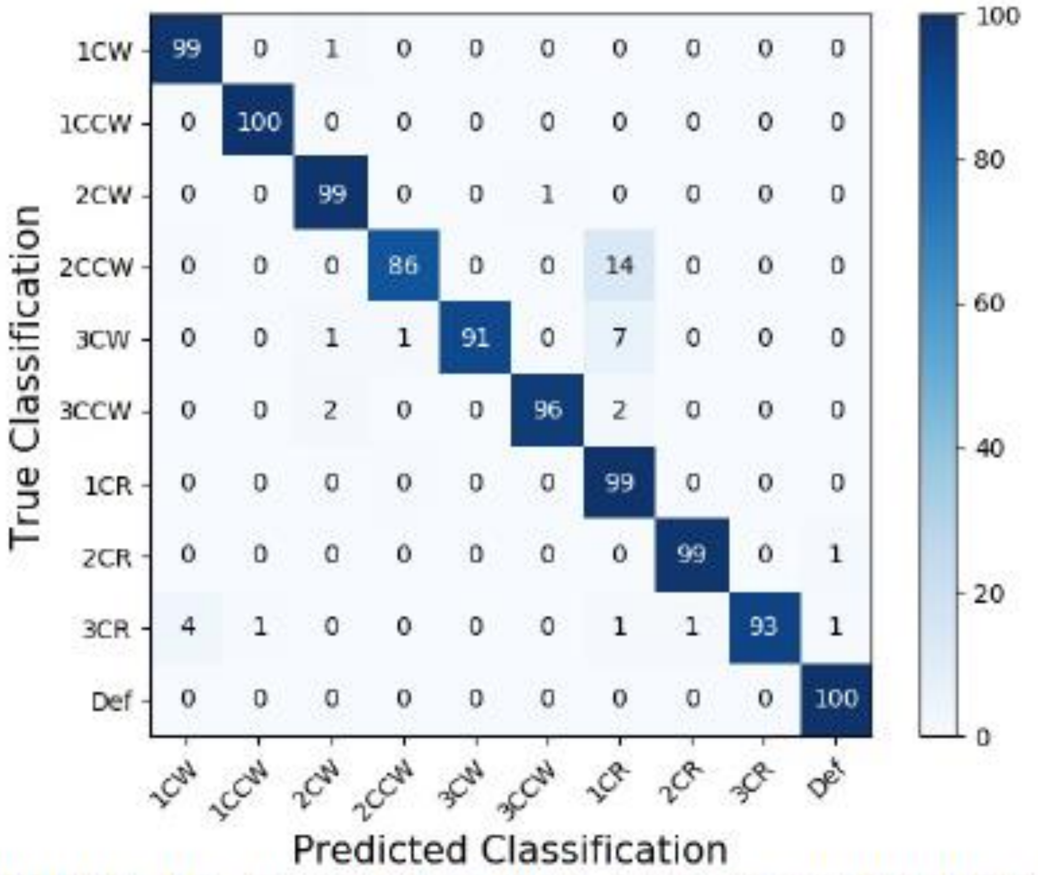
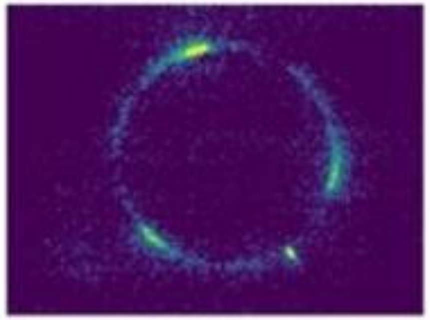


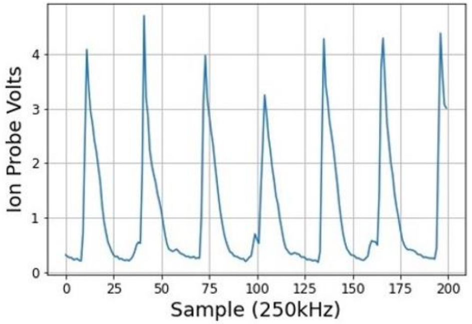
FIGURE 16: Normalized confusion matrix of extended dataset containing counter-rotating waves and deflagrative behaviors

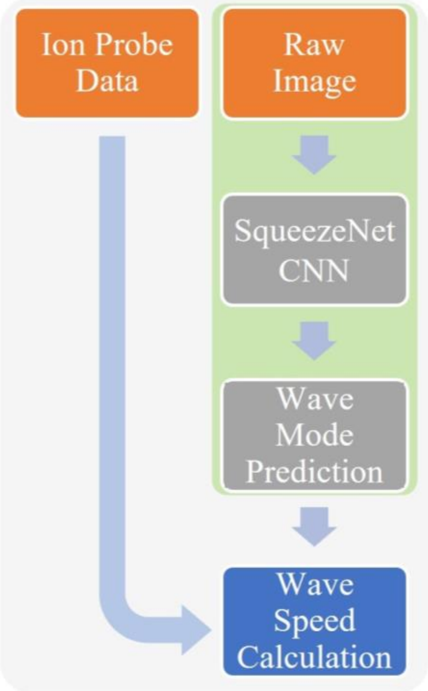
Johnson, Kristyn B, Donald H Ferguson, Robert S Tempke, and Andrew C Nix. “Application of a Convolutional Neural Network for Wave Mode Identification in a Rotating Detonation Combustor Using High-Speed Imaging.”, GT2020-15676 In ASME 2020 Turbo Expo. Virtual, Online: ASME Turbo Expo, 2020.

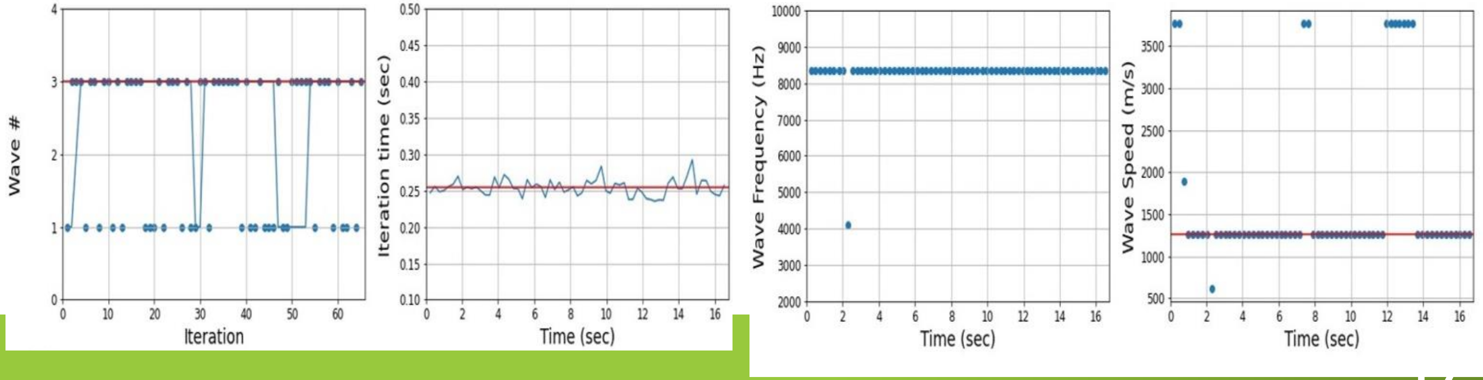
Real-Time Lab Deployment

- **Data acquired and managed in Python**
- **Initialization steps**
  1. SqueezeNet Model pre-loaded
  2. Connection to camera and cDAQ
  3. Empty variables initialized
- **Iterative steps**
  1. Camera triggered by Pylon
  2. Ion probe data read through PyDAQ
  3. Classification and calculation
  4. Diagnostic output plotted



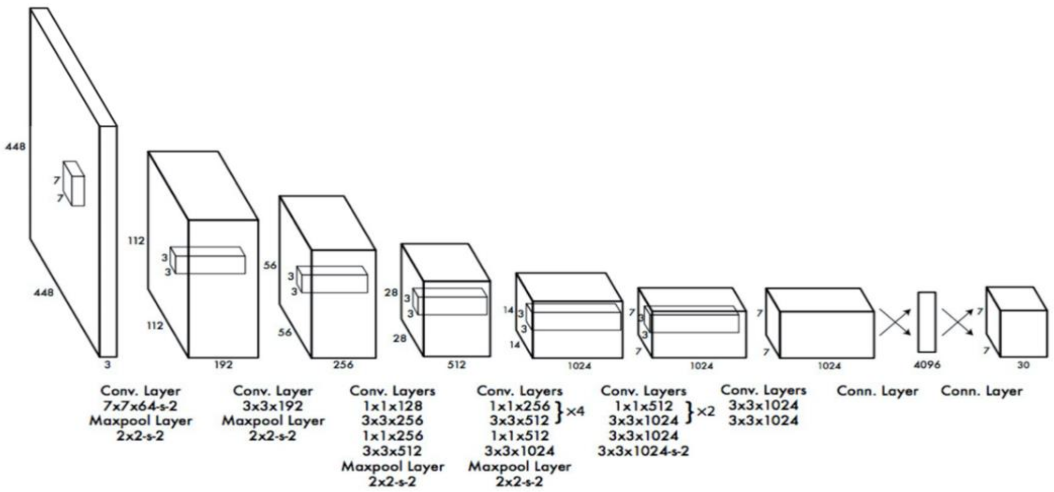


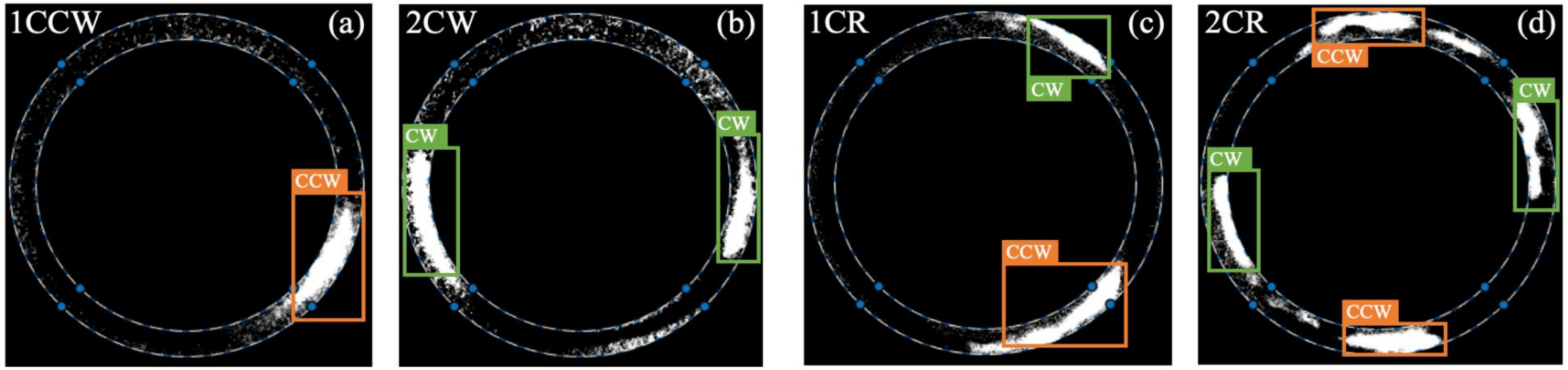




Computer Vision Object Detection applied to High-Speed Images

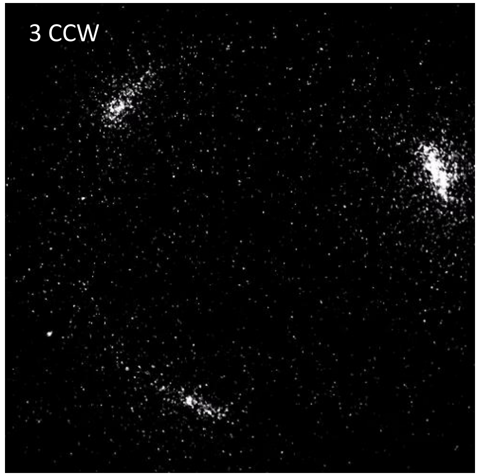
- Wave profiles offer intensity features suggesting wave direction
- Features can't be "hard-coded"
- Convolutional Neural Networks (CNN) can perform feature extraction
  - You Only Look Once (YOLO)
    - Object detection network

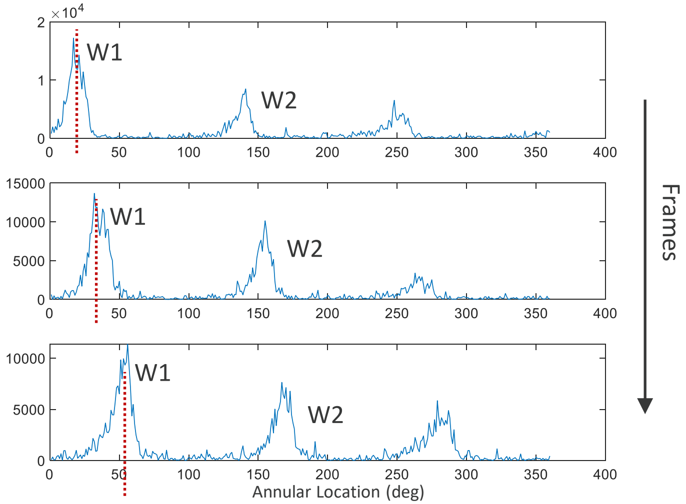


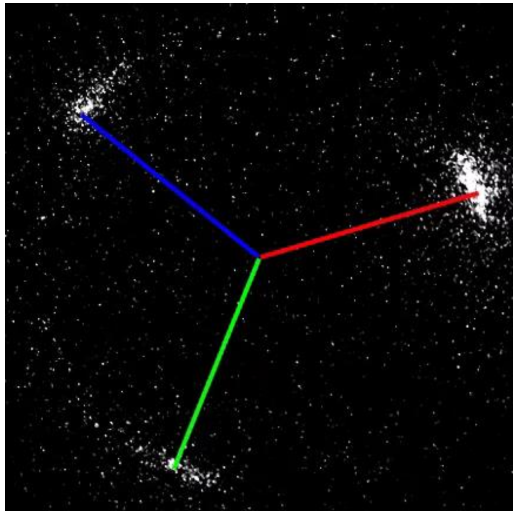


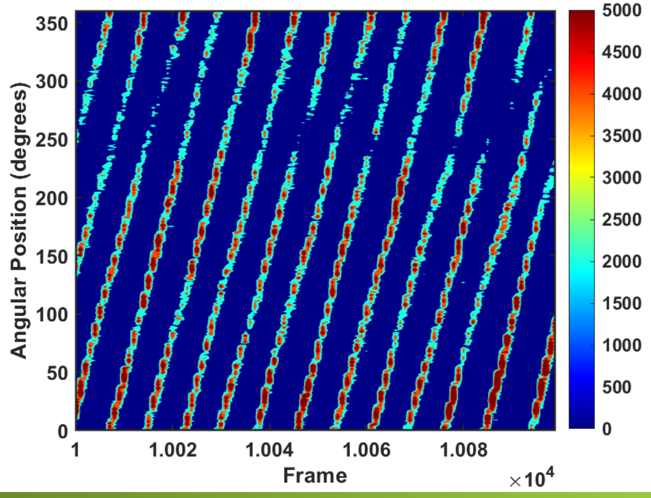
Detonation Wave Tracking through Object Detection

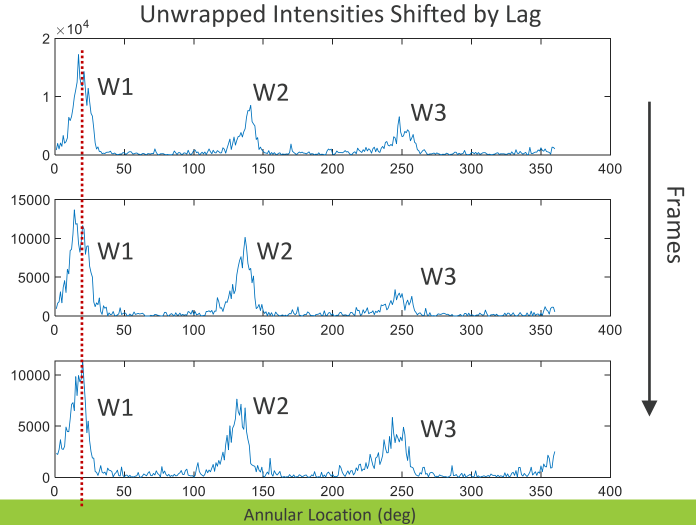
Alternative Image Analysis – Galloping Waves

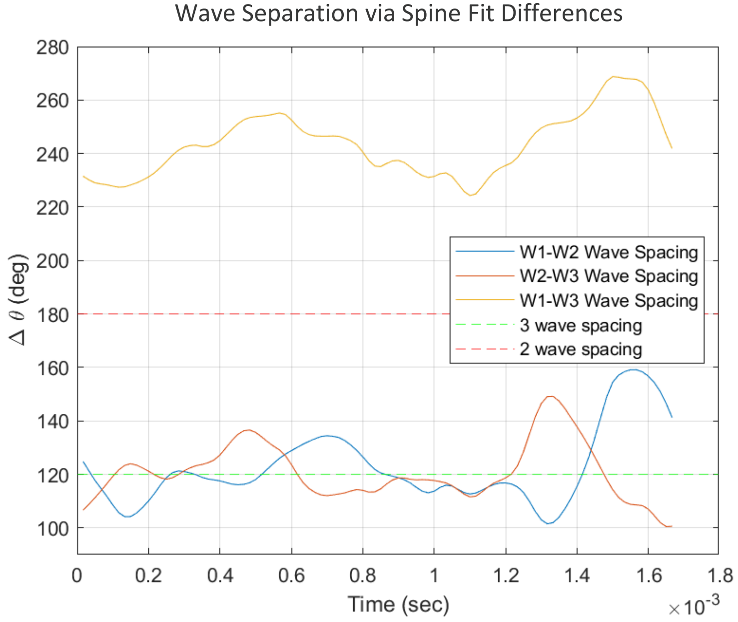






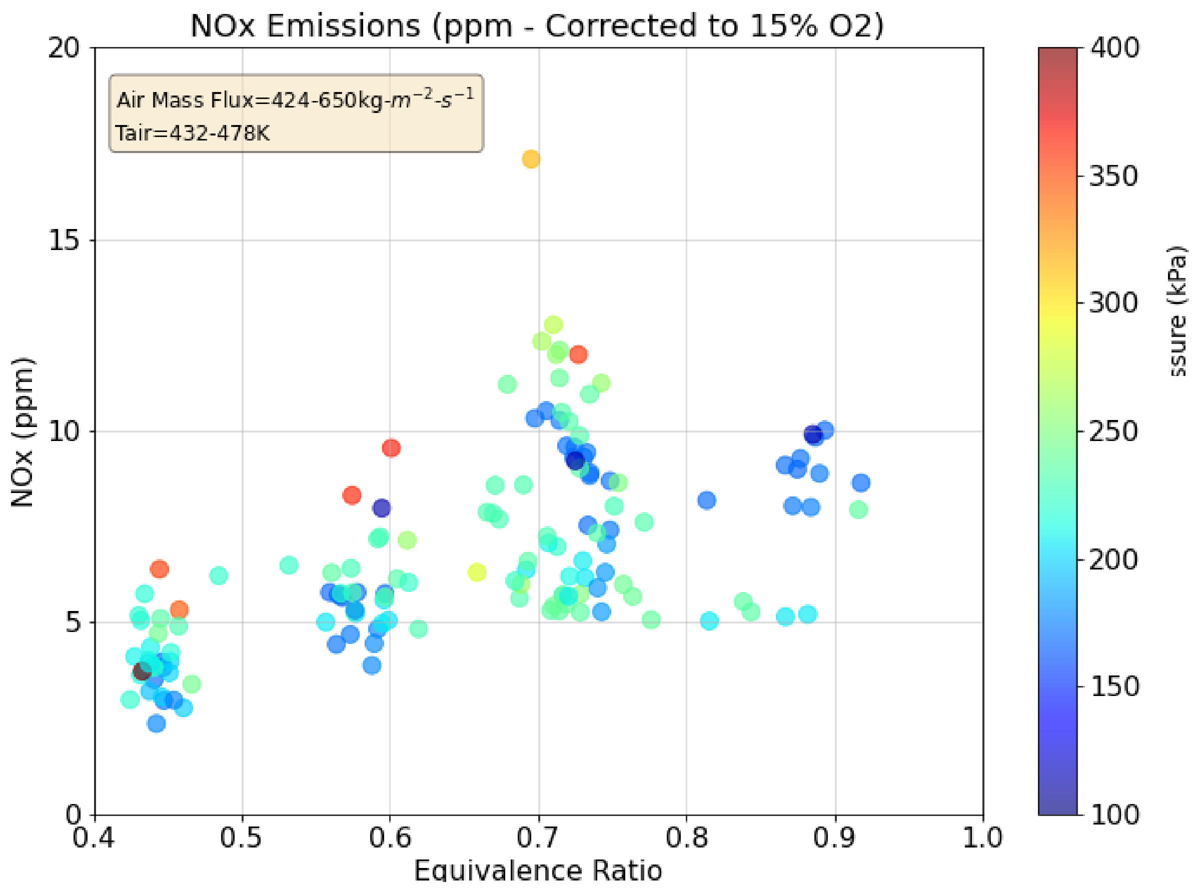




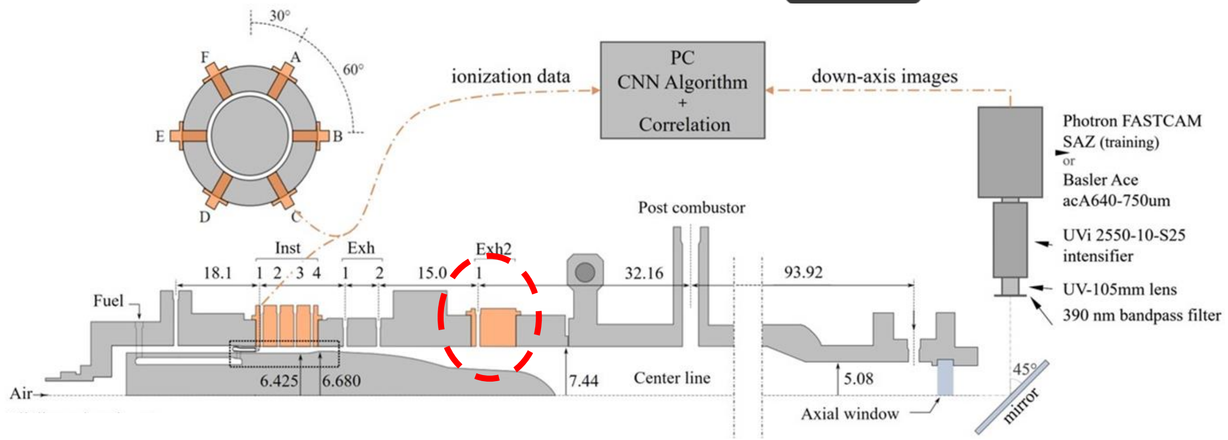


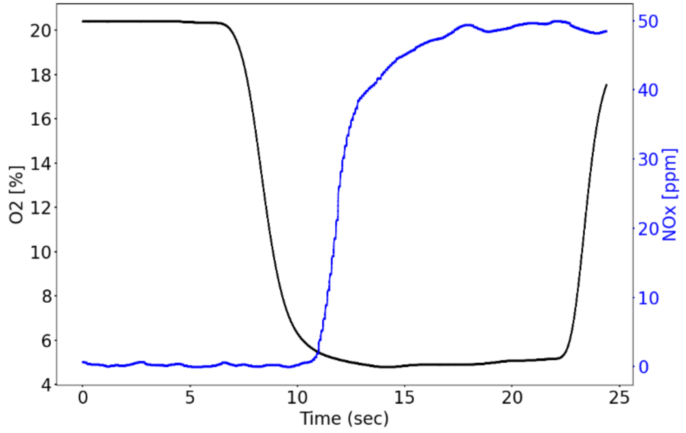
NOx Emission (ppm) – NETL RDE on H2-Air

NOx Emissions (ppm) – Corrected to 15% O2



$$Oxygen\ referenced\ conc. = Measured\ conc.x\ \frac{20.9 - Oxygen\ Reference\ value\ (\%)}{20.9 - measured\ oxygen\ (\%)}$$





P_{back} = 175 kPa

mflx = 620 kgm^{-2}s^{-1}

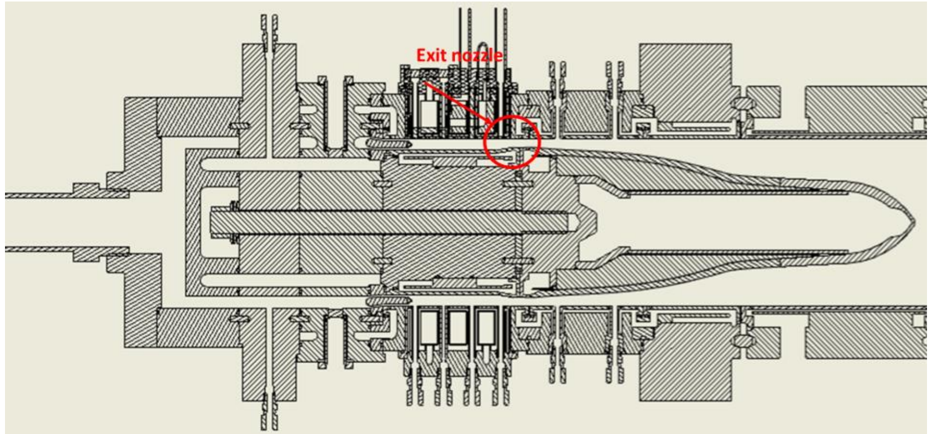
phi = 0.8, T_{air} = 435K

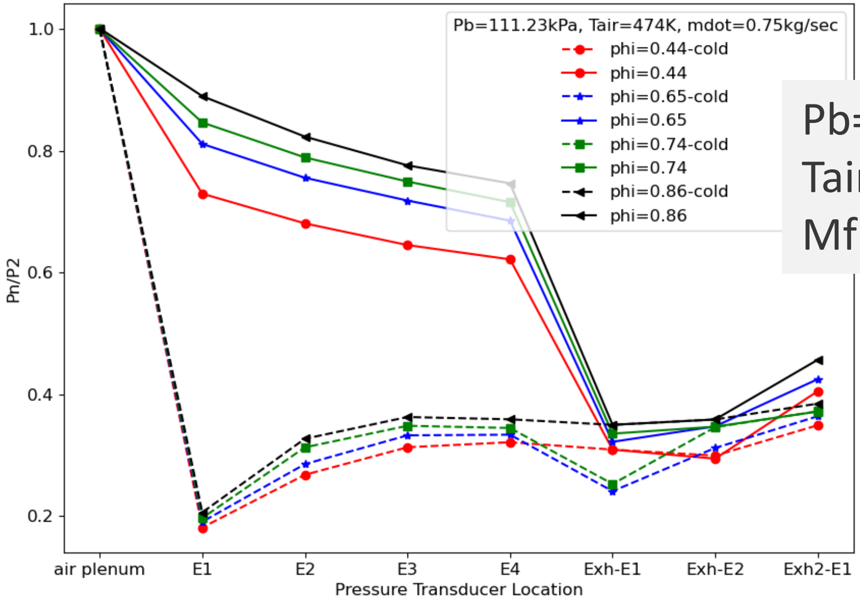
1. NOx Analyzer (1 sec response)
2. O2 Analyzer
3. Gas Sample Storage Tanks (x3)
4. Gas sample line

Ferguson, Donald H., Bridget O'Meara, Arnab Roy, and Kristyn Johnson. "Experimental Measurements of NOx Emissions in a Rotating Detonation Engine.", AIAA2020-0204, *AIAA Scitech 2020 Forum,* Orlando, FL, January 2020, https://doi.org/10.2514/6.2020-0204.

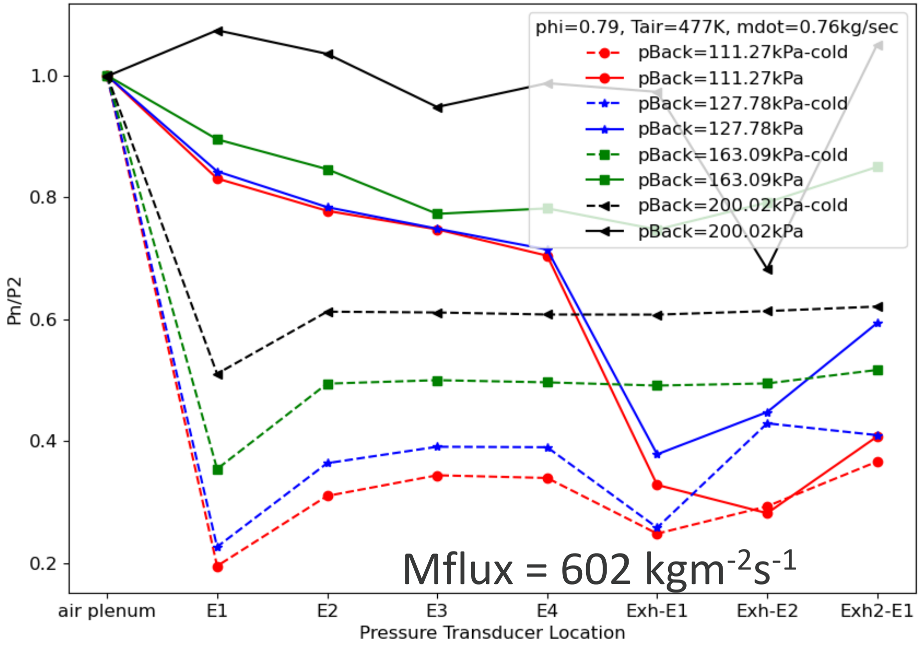
NETL Water-Cooled, High Pressure RDE

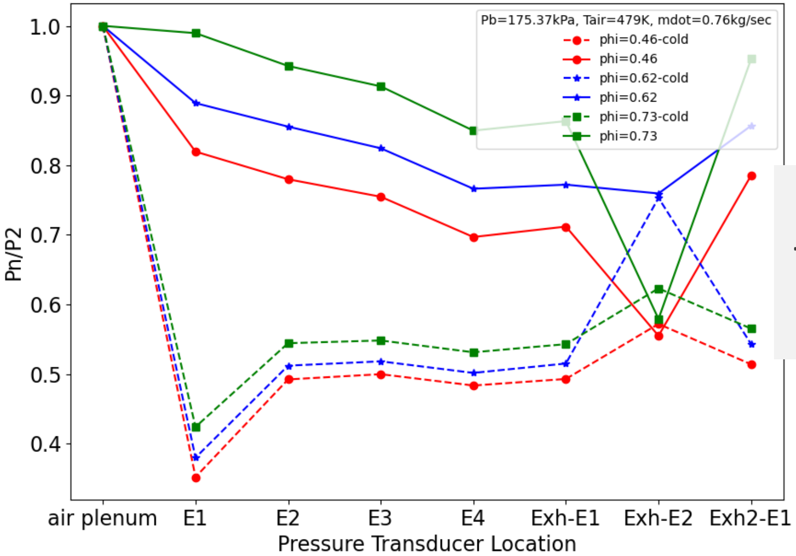
Choked vs Unchoked Exit Nozzle





Pb=111.2 kPa
Tair = 474K
Mflux = 594 $kgm^{-2}s^{-1}$





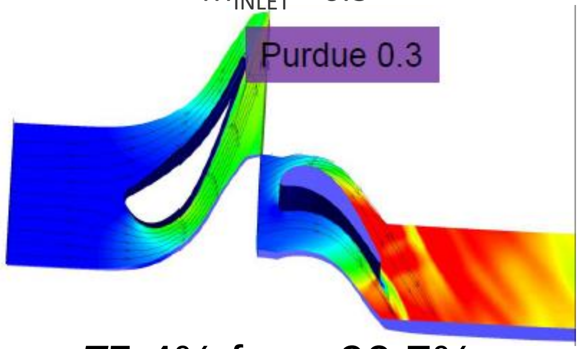
Pb=175.3 kPa
Tair = 473K
Mflux = 602 $kgm^{-2}s^{-1}$

Turbine Integration – High efficiency Diffuser

Guillermo Paniagua and James Braun (Purdue University)

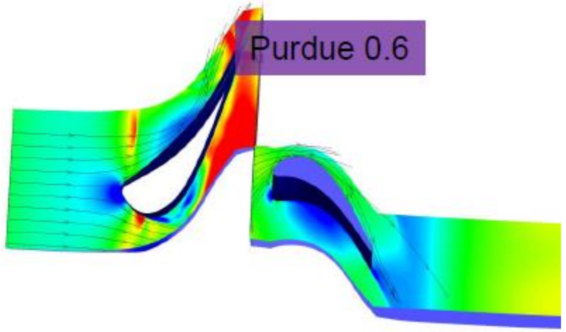
At large amplitude e*fficiency is reduce*

$M_{INLET} = 0.3$

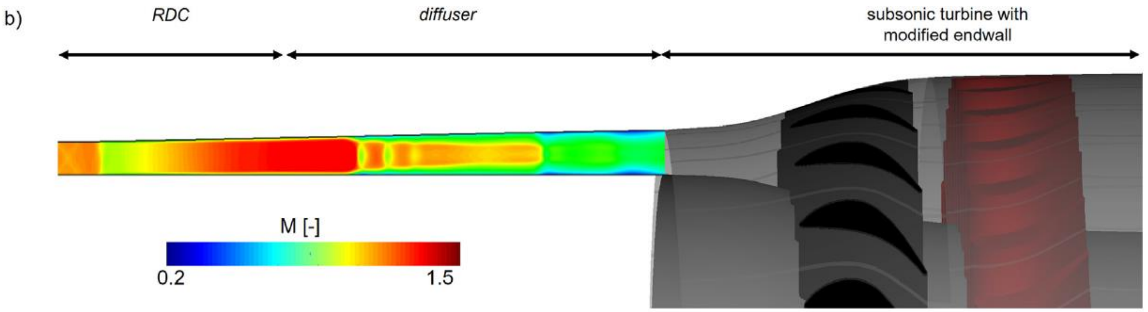


75.4% from 90.7%

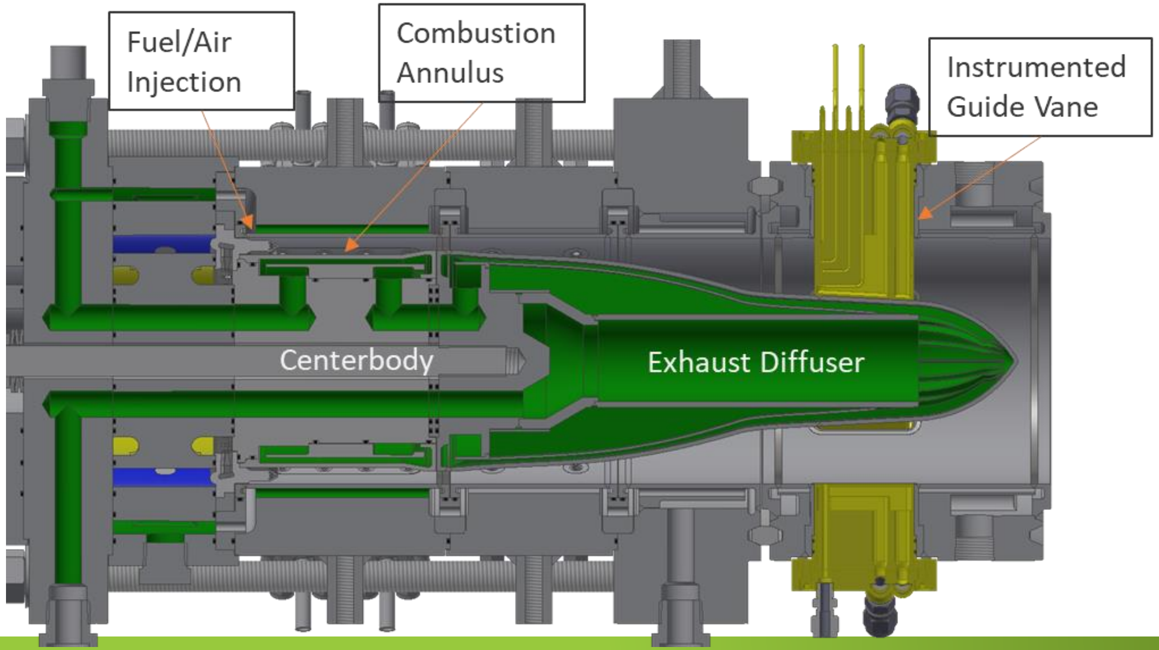
$M_{INLET} = 0.6$



71.7% from 79.7%



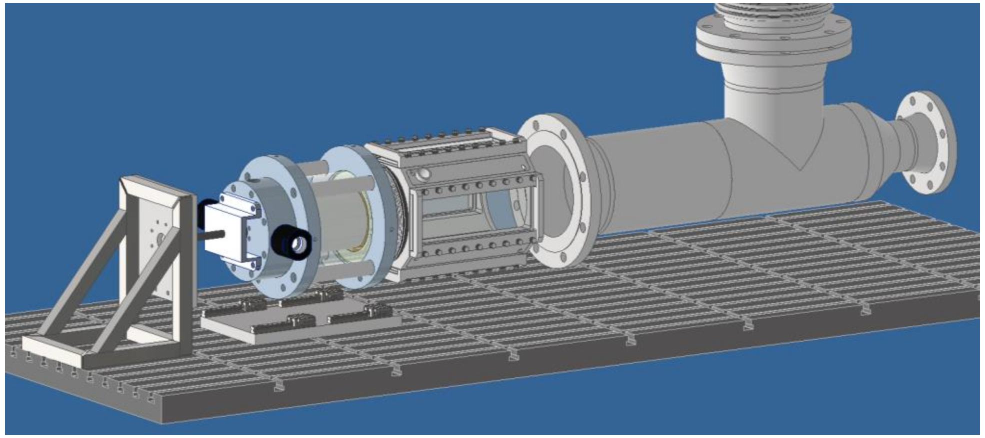
Liu et al., "Thermal power plant upgrade via a rotating detonation combustor and retrofitted turbine with optimized endwalls", Intl J. of Mech Sci,V188 (2020), https://doi.org/10.1016/j.ijmecsci.2020.105918

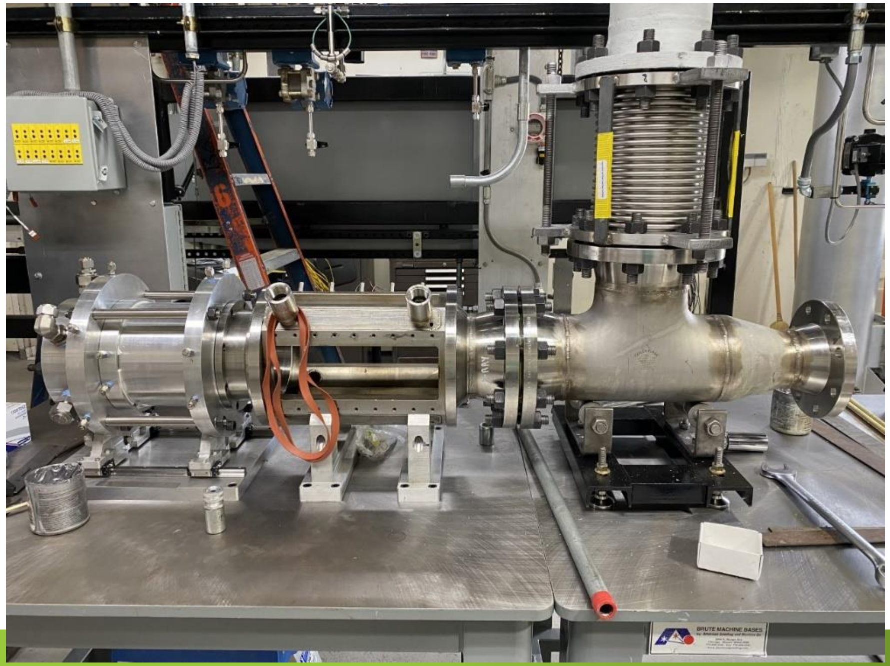


NETL Optical and Modular RDE (mRDE)

Combustor-Plenum interactions and Combustion Stability

- **Optical Access**
  - Air plenum, combustor and exhaust
- **Thrust measurement with ducted exhaust**
  - Provides performance metric through Equivalent Available Pressure (EAP)
  - Working to develop performance metric for turbomachinery
- **Testing conditions**
  - Hydrogen-Air (sonic nozzle flow measurement)
  - Short duration (~ 3 sec)
  - m_{air} = 0-0.61 kg/sec
- **Full diagnostic compliment**
  - OH Chemi, TDLAS, high speed PLIF/PIV, P, T and chemi ionization (ion probe)





Summary

NATIONAL ENERGY TECHNOLOGY LABORATORY

- **DOE focus is on RDE-gas turbine integration**
  - Improved cycle efficiency, H_2-Air combustion and potential for low NOx emissions.
  - PGC is inherently unsteady, fuel-oxidizer mixing, turbine inlet Mach #, characterize cycle benefits, high heat flux

- **NETL-RIC RDE focus**
  - Impact of wave mode, reduce combustion losses associated with deflagration
  - Maximize work availability at the turbine inlet
  - Control NOx emissions
  - Improve turbulent combustion models

- **NETL High-Pressure RDE focus**
  - Instrumented nozzle guide vane tests

- **NETL Optical RDE**
  - Influence of injector on combustion losses
  - Performance characterization

Thank You.

Questions??

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NATIONAL ENERGY TECHNOLOGY LABORATORY

U.S. DEPARTMENT OF ENERGY