Advanced Cost-effective Coal-Fired Rotating Detonation Combustor for High Efficiency Power Generation

DE-FE0031545

Kareem Ahmed[1], Subith Vasu[1], Suresh Menon[2]
[1]University of Central Florida, Orlando, FL
[2]Georgia Tech, Atlanta, GA

PM: Dr. Seth Lawson, TM: John Rockey

Industry Partners: Aerojet Rocketdyne (Dr Scott Claflin)
ISSI (Dr. John Hoke)
AFRL (Dr. Fred Schauer)
Siemens (Timothy Godfrey)

NETL CO2 Capture Technology Project Review
August 14th, 2018

Outline

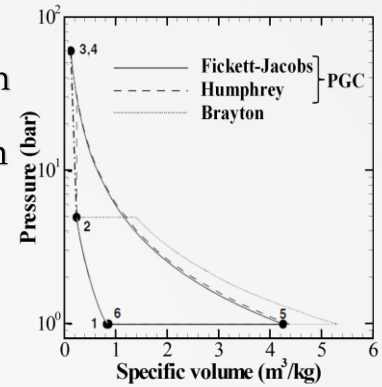
- Background
- Project Objectives
- Technical Approach
- Project Structure and Management
- Project Schedule

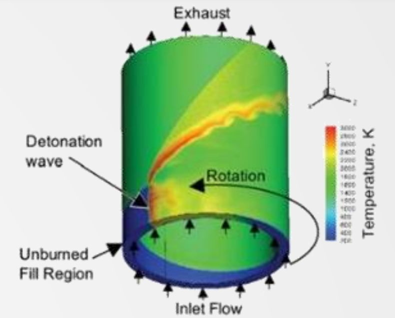
Pressure Gain Combustion

Detonation

- Exploits pressure rise to augment high flow momentum
- Fundamental mechanism is turbulent flame acceleration
- High flow turbulence intensities and length scales
- Serious challenge for reliable, repeatable and efficient

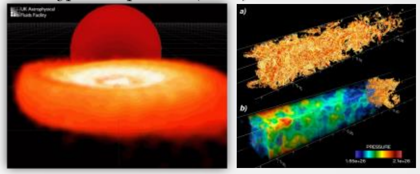
Thermodynamic Cycle





Schwer, *et al.*, AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit. 2010

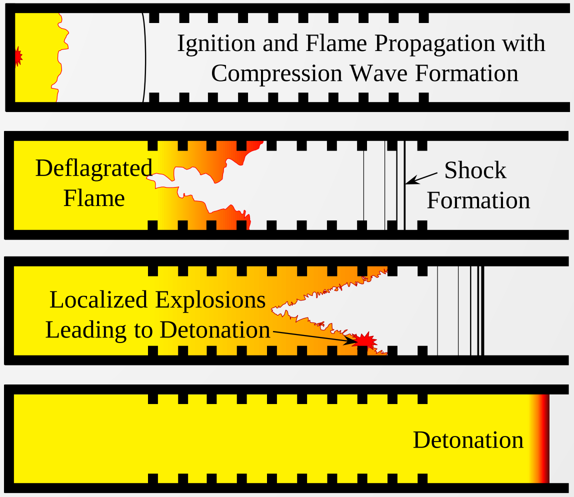
Relate to Type Ia Supernovae (SNIa) – Thermonuclear Flames



Deflagration-To-Detonation Transition Process

1. Ignition of a deflagration flame
2. Turbulent flame acceleration due to turbulent mixing
3. Transition:
   - Reflected shock (*Oran et al.*)
   - Localized vortical explosion (*Zeldovich gradient mechanism*)
   - Boundary layer turbulence (*Oppenheim*)
   - Turbulence-Driven DDT (*UCF-NRL*)
4. Formation of a self-sustaining detonation wave

Deflagration-To-Detonation Process



Why Detonation for Coal ACS?

Origin of Detonation:

- Detonation first discovered during disastrous explosions in coal mines, 19^{th} century.
- Puzzling at first, how the slow subsonic combustion could produce strong mechanical effects. *Michael Faraday "Chemical History of a Candle" 1848*
- First detonation velocity measurement, Sir Frederic Abel 1869
- Coal particles and coal gas interaction, Pellet, Champion, Bloxam 1872
- Berthelot hypothesized shock wave reaction, detonation, 1870

Museum of Industry, Drummond Mine Explosion, 1873

Coal Mine Fast-Flame Deflagration Explosion

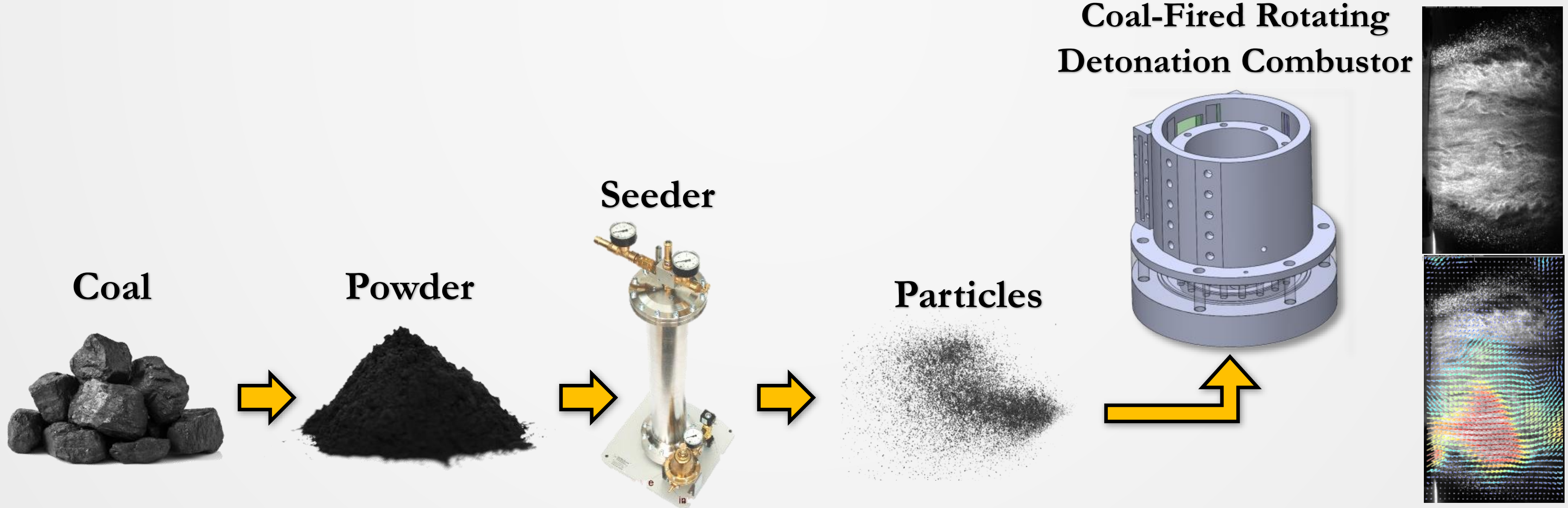
Coal Mine Detonation Explosion

Project Objectives

Explore Advanced Cost-Effective Coal-Fired Rotating Detonation Combustor:

The proposed project aims to characterize the operability dynamics and performance of an advanced cost-effective coal-fired rotating detonation combustor for high efficiency power generation

- Development of an operability map for coal-fired RDC configuration
- Experimental investigation and characterization of coal-fired combustor detonation wave dynamics
- Computational investigation and characterization of coal-fired combustor detonation wave dynamics
- Measurement and demonstration of pressure gain throughout the coal-fired RDC operational envelope
- Measurement and demonstration of low emissions throughout the coal-fired RDC operational envelope



Project Objectives

1. Operability Dynamics for Detonation Wave:
   a. *Coal Injection:* what is the coal particle size, effective volume fraction, and seeding technique? *The focus here will be on effective refraction/burning rate and detonation-solid interaction.*
   b. *Initiation:* is the reaction front that is formed a detonation or a deflagration flame that is acoustically coupled? *The focus here will be on the mechanisms of deflagration-to-detonation transition and composition enrichment syngas and oxy-coal rotating detonation combustion.*
   c. *Directionality:* which direction do the waves rotate and why? why and when do they change direction? *The focus here will be on the conditions and mechanisms of detonation wave direction.*
   d. *Bifurcation:* How many waves are generated and why? *The focus here will be on the driving mechanisms of the form of detonation wave topology.*

2. Performance:
   a. *Pressure Gain:* How much pressure gain is generated under steady and dynamic operability? *The focus here will be on the direct measurement of pressure gain production.*
   b. *Emissions:* what level of emissions coal RDC generate under steady and dynamic operability? *The focus here will be on the direct measurement of emissions along with modeling.*

Project Management

Roles of Participants

DOE ACS Management

University of Central Florida
(Prime Recipient)

Dr. Kareem Ahmed
Dr. Subith Vasu

Aerojet Rocketdyne
(Industry Partner)

Dr. Scott Claflin

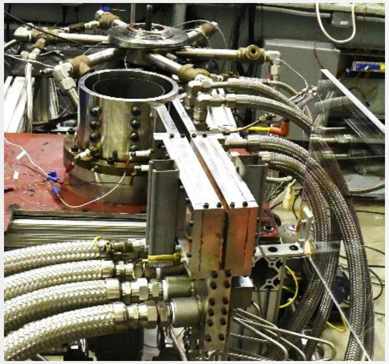
Georgia Institute of Technology
(Sub-Recipient)

Dr. Suresh Menon

Innovative Scientific Solutions, AFRL
(Industry Partner)

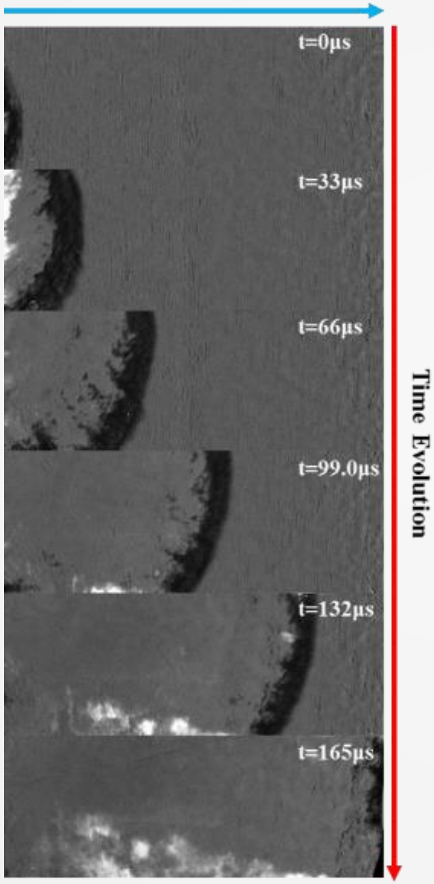
Dr. John Hoke
Dr. Fred Schauer

Rotating Detonation Engine in Supersonic Flow



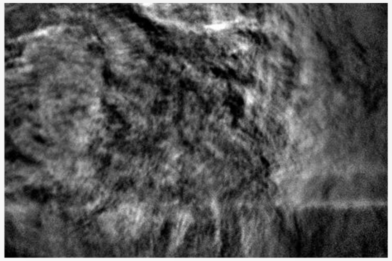
Detonation Propagation in a Premixed Supersonic Flow

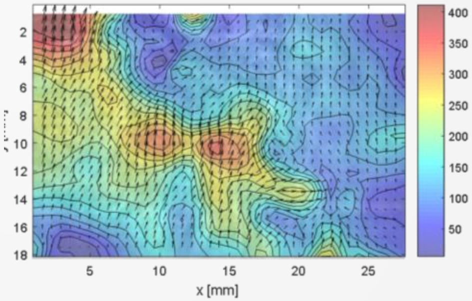
Flow Direction



J. Sosa *et al*, AIAA Aerospace Sciences Meeting, 2018.

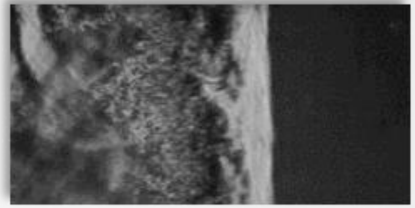
RDE Exhaust Velocimetry



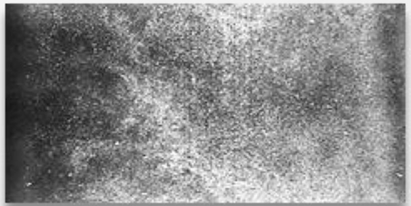


Detonation wave velocimetry and structure conducted at Dr. Ahmed's UCF lab

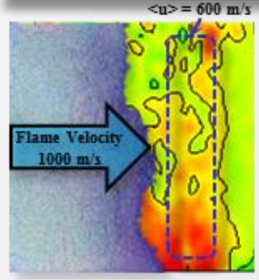
Detonation Shock-Particle-Flame Flow



Aluminum Oxide Particles Flow

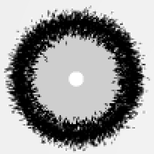


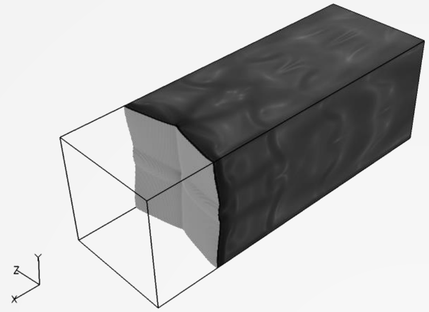
Detonation Turbulent Flame



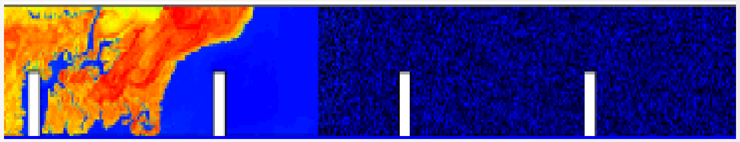
J. Chambers *et al*, ICDERS, 2017

Pressure Gain Combustion

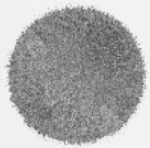


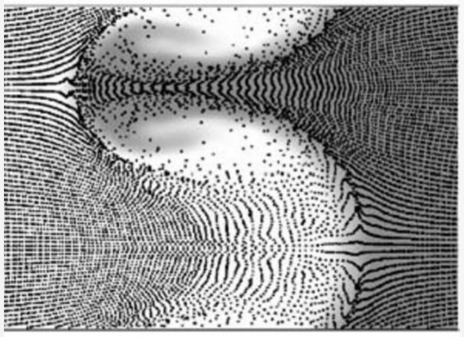


Steady 3D Detonation in a channel



DDT in two-phase channel with obstacles





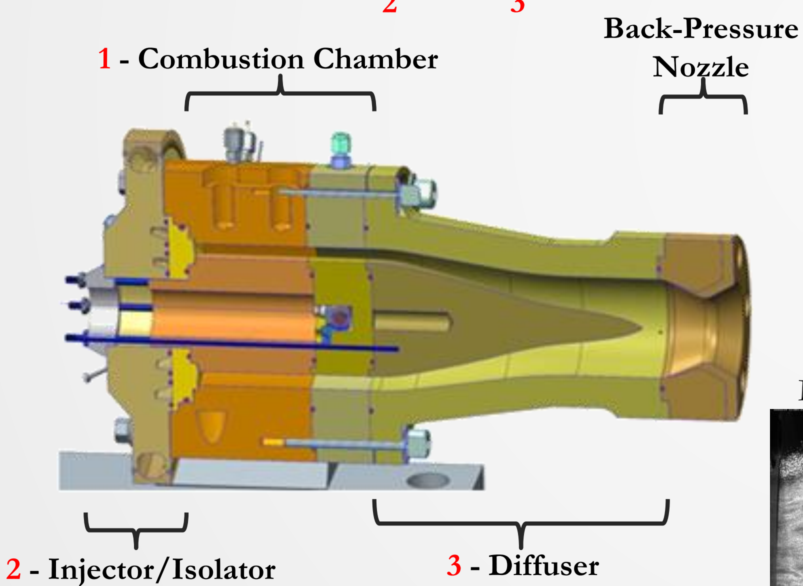
Detonation charge surrounded by inert steel particles

- Research focused on confined and free detonation
- Simulations with inert and reactive (Al) particles
- Condensed phase and gas phase detonation
- Deflagration-to-Detonation Transition (DDT)
- Code LESLIE in AFRL (Eglin) for detonation studies
- http://www.ccl.gatech.edu

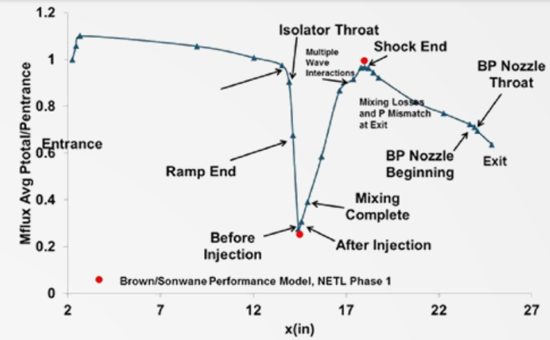
Vision

The goal is to measure stagnation pressure for fundamental understanding of pressure gain within a rotating detonation engine. This will allow for proper understanding of flow field effects.

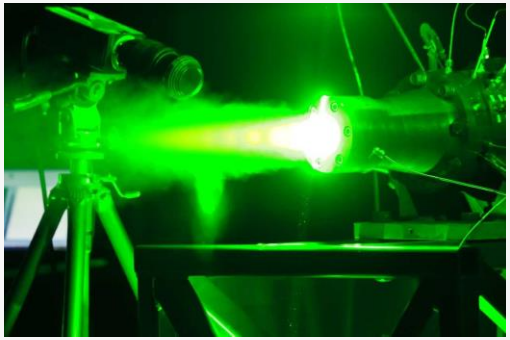
$$\left(\frac{\hat{P}^o_{d,ex}}{\hat{P}^o_M}\right) = \frac{\left(\frac{\hat{P}^o_{c,ex}}{\hat{P}^o_{c,in}}\right)_1}{\left(\frac{\hat{P}^o_M}{\hat{P}^o_{c,in}}\right)_2\left(\frac{\hat{P}^o_{c,ex}}{\hat{P}^o_{d,ex}}\right)_3}$$



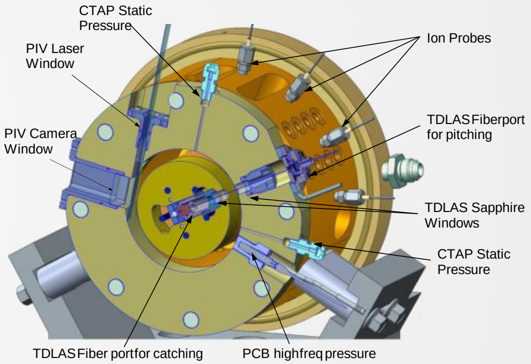
Aerojet Rocketdyne RDE cutout



Computed pressure gain through engine

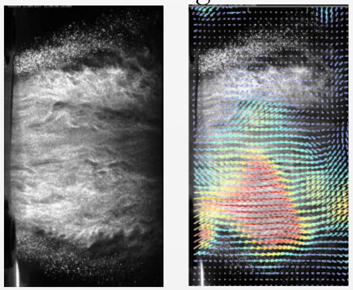


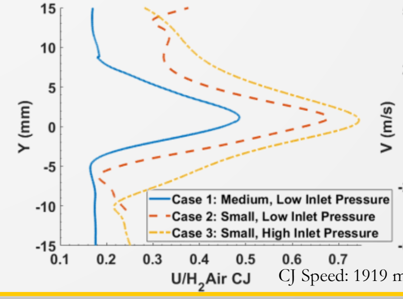
PIV on exit plane of nozzle of the Aerojet RDE



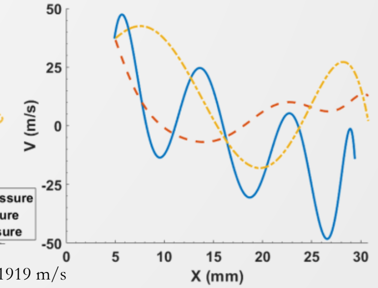
Entire CAD of Aerojet RDE cutout sitting on static test fire stand

Mie Scattering Particles



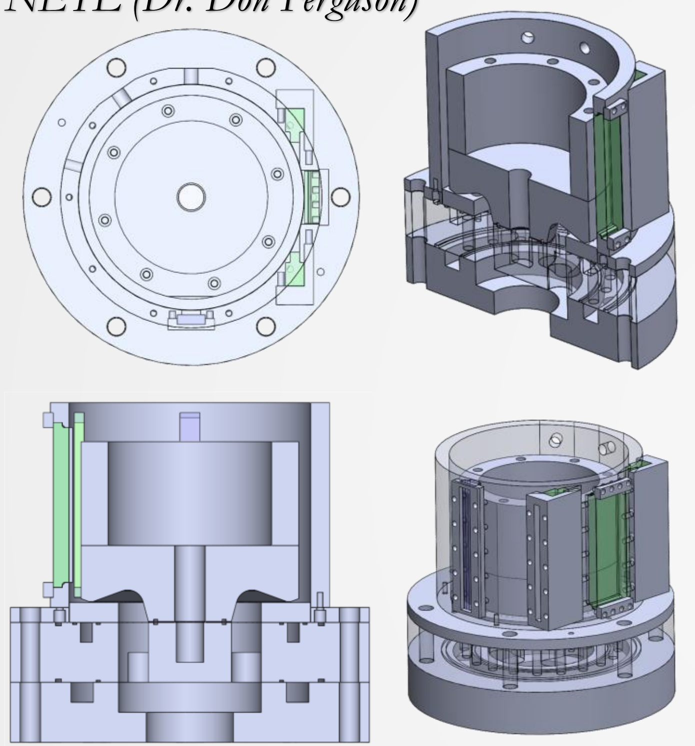


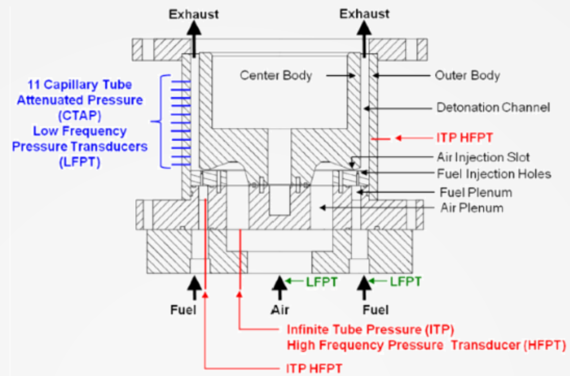
CJ Speed: 1919 m/s

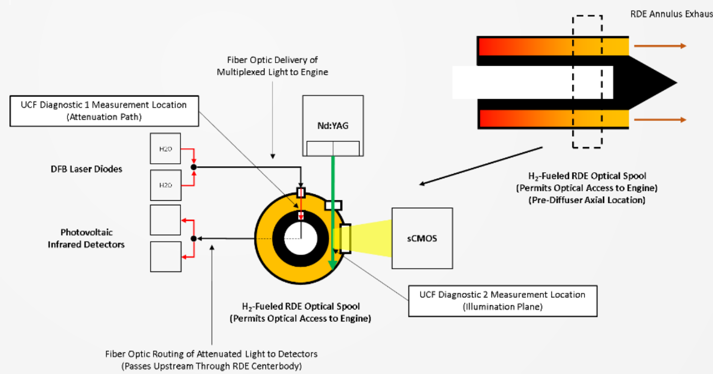


Coal Rotating Detonation Combustor

Coal Rotating Detonation Combustor: *Modeled After the AFRL RDE and the NETL (Dr. Don Ferguson)*

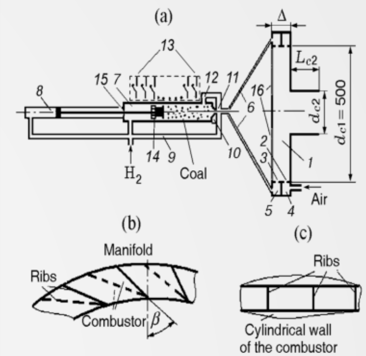


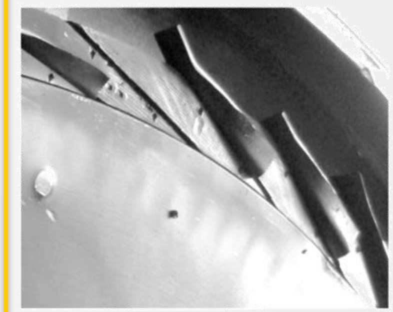


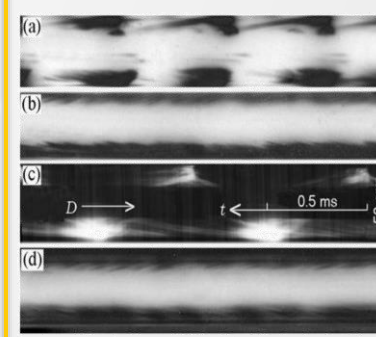


J. Sosa *et al*, AIAA Aerospace Sciences Meeting, 2018.

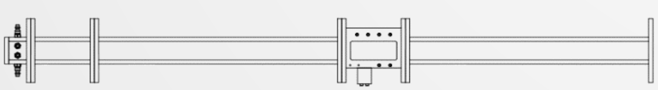
Russia: Bykovskii *et al.* 2013



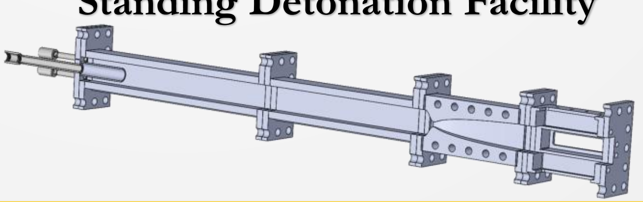




Deflagration-to-Detonation Facility



Standing Detonation Facility



Combustible Solid Particles

Characterization of Materials

Experimental minimum tube diameter and K_{ST}-factor

Dust	Size	K_{ST}	d_{min}
	μm	bar·m/s	m
U.S. W. Sub-Bituminous coal[a]	≤ 100	59[b]	0.6
Cornstarch	10	160	0.3
Anthraquinone	$22 \times 6 \times 6$	274	0.14
Aluminum	$36 \times 36 \times 1$	359	0.12

Note: *a* - Gardner et al. (1986); *b* - Fangrat et al. (1987).

F. Zhang *et al.*, *Journal of Shock Waves,* 2001

Potential:

Carbon Black (very fine)

Cannal Coal (Russians coal of choice)

Aluminum Iodate Hexahydrate (for doping)

Liquid Isopropyl nitrate (for doping, need a new injection scheme

ASBURY CARBONS

Bituminous Coal, Anthracite Coal, Carbon Black

(All coal sizes as low at 75 micrometers with the exception of carbon black. Carbon black can be found as low as 18 nanometers)

SIGMA-ALDRICH

Anthraquinone Powder, Aluminum Nanoparticles, Liquid Isopropyl nitrate

Combustible Solid Particles (C3)

Bit Coal

Asbury provides LOW SULFUR Bituminous Coal commonly known as Bit Coal. This material is ground and screened to specifications commonly used for foundry sand addition, brake linings and other industrial applications.

Chemistry

	TARGET MIN	TARGET MAX	C3 TYPICAL	D4 TYPICAL
% SULFUR	0	1	0.71	0.74
% VOLATILE	34	44	37.4	38.6
% MOISTURE	0	7	5.2	3.4
% ASH	0	10	8	7.1
% FIXED CARBON	50	60	54.6	54.3

The percentages above/below are "Targets" and not meant to be a guarantee.

Sizing

Product	US Standard Sieves in % Mesh						
	+16 (1.18mm)	+20 (850 Microns)	+30 (600 Microns)	+40 (425 Microns)	+100 (150 Microns)	+200 (75 Microns)	-200 (75 Microns)
C3 Target	0	2 - 9	6 - 18	8 - 15	27 - 36	------------	max 27.5
C3 Typical	0	7.5	16	14.9	32	12.7	16.9
D4 Target	------------	0 - 1	1 - 12	5 - 16	28 - 46	14 - 27	12 - 40
D4 Typical	------------	0.3	3.9	7.2	37.3	21	30.3

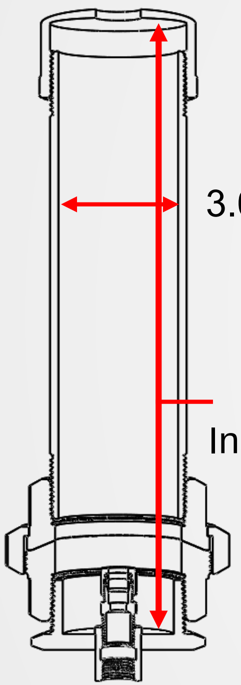
- Packaging includes 50 lb bags or 2000 lb super sacks.
- Export Packaging and containerization available.
- Shipping to any port destination.

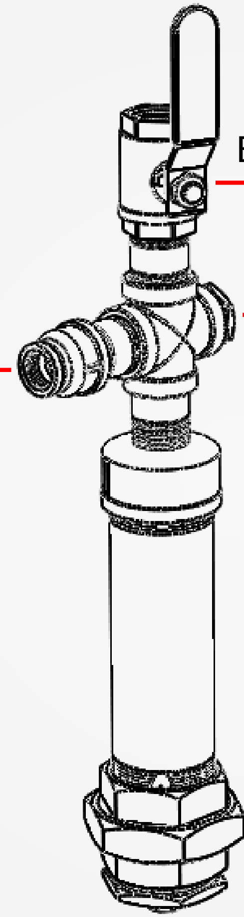
In the US or abroad…

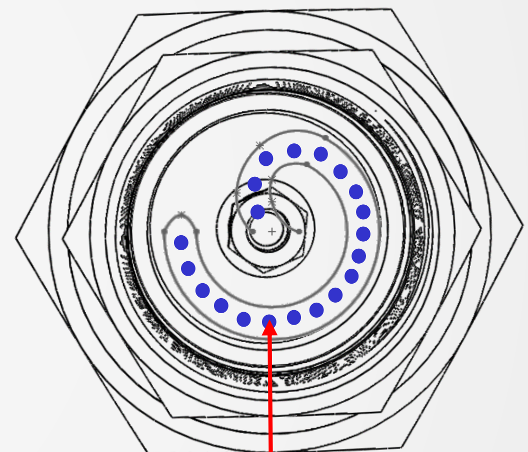
Let Asbury handle your Bit Coal requirements

ASBURY CARBONS
An ISO 9001 Corporation
ASBURY GRAPHITE MILLS, INC.
405 Old Main Street • PO Box 144 • Asbury, New Jersey 08802
Phone: 908.537.2155 • Fax: 908.537.2908
www.asbury.com

Seeder Design

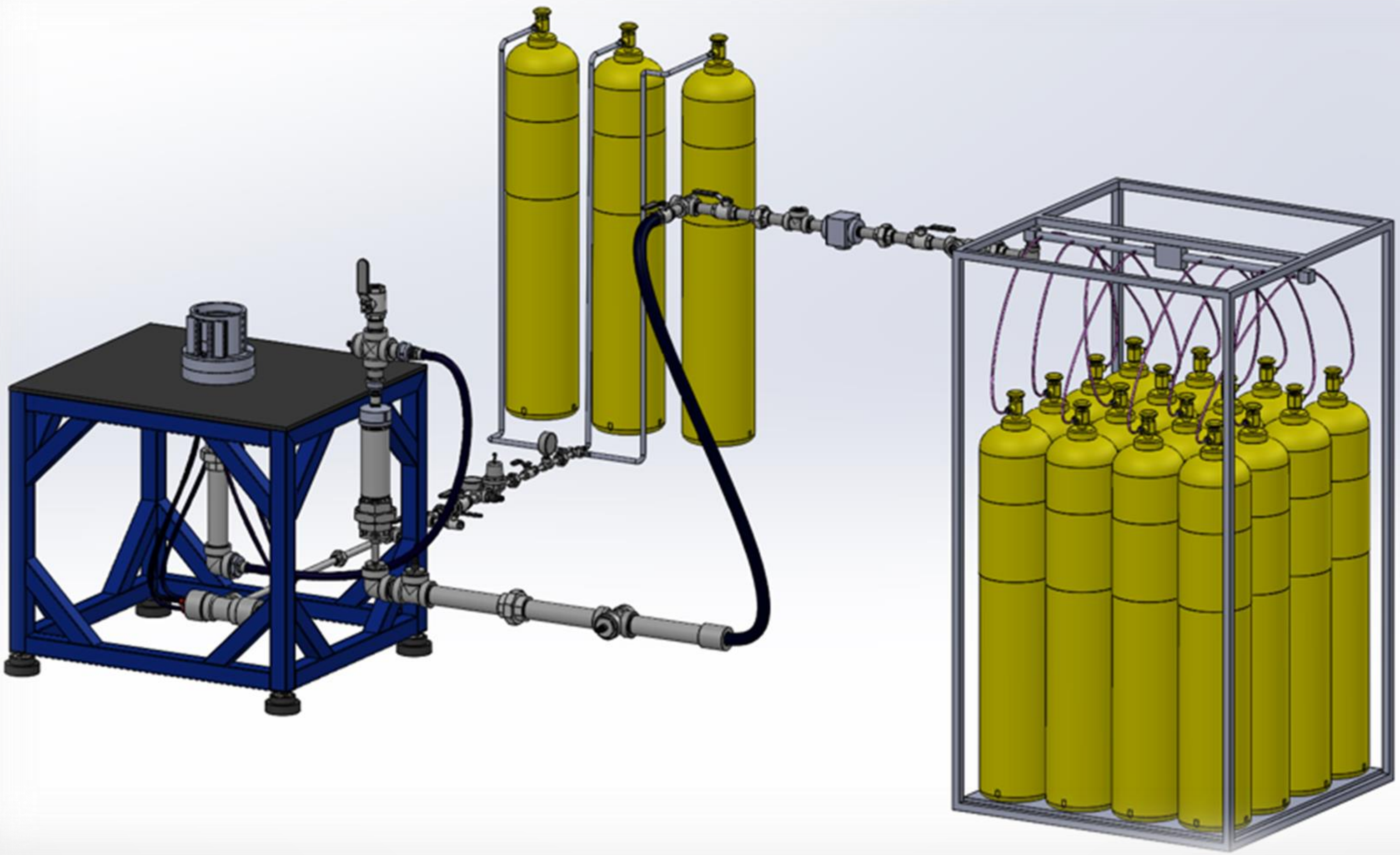






Seeder inline with air, downstream of Sonic Orifice

Facility



Facility

Hydrogen Tanks

Hydrogen Line

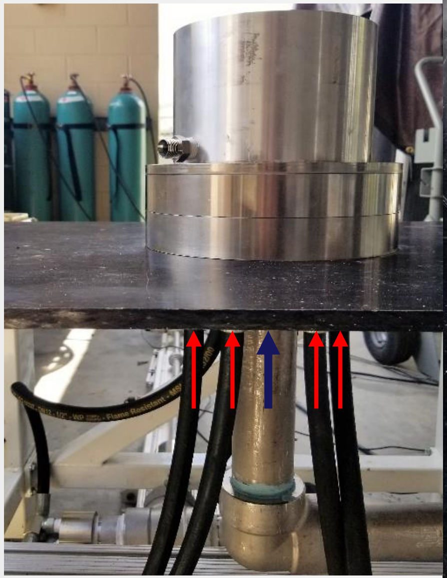
RDE

Pre-Det Tanks

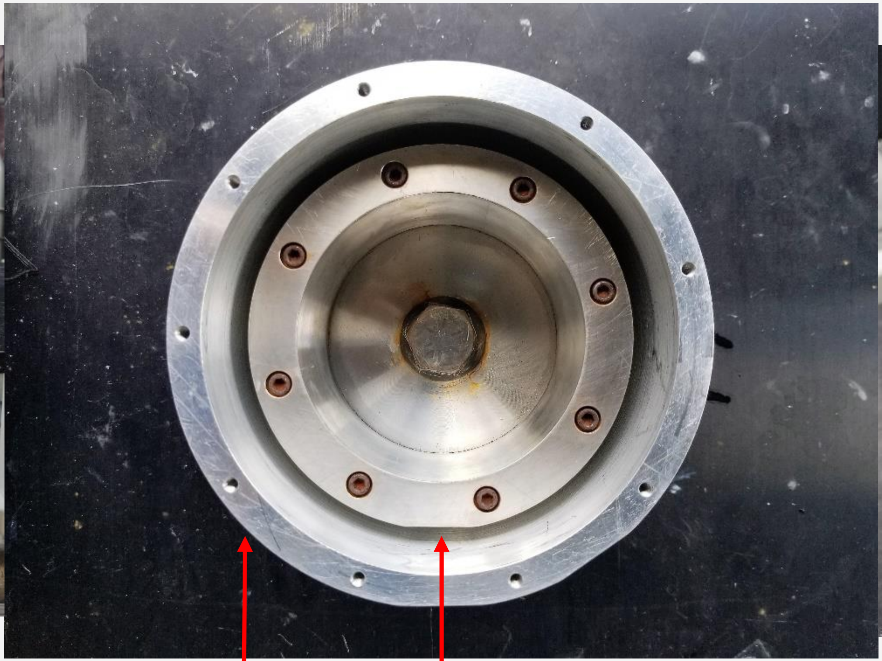
Air Tanks

Air Line

RDE



Manifold Connections
Red: Hydrogen, 6 in total
Blue: Air

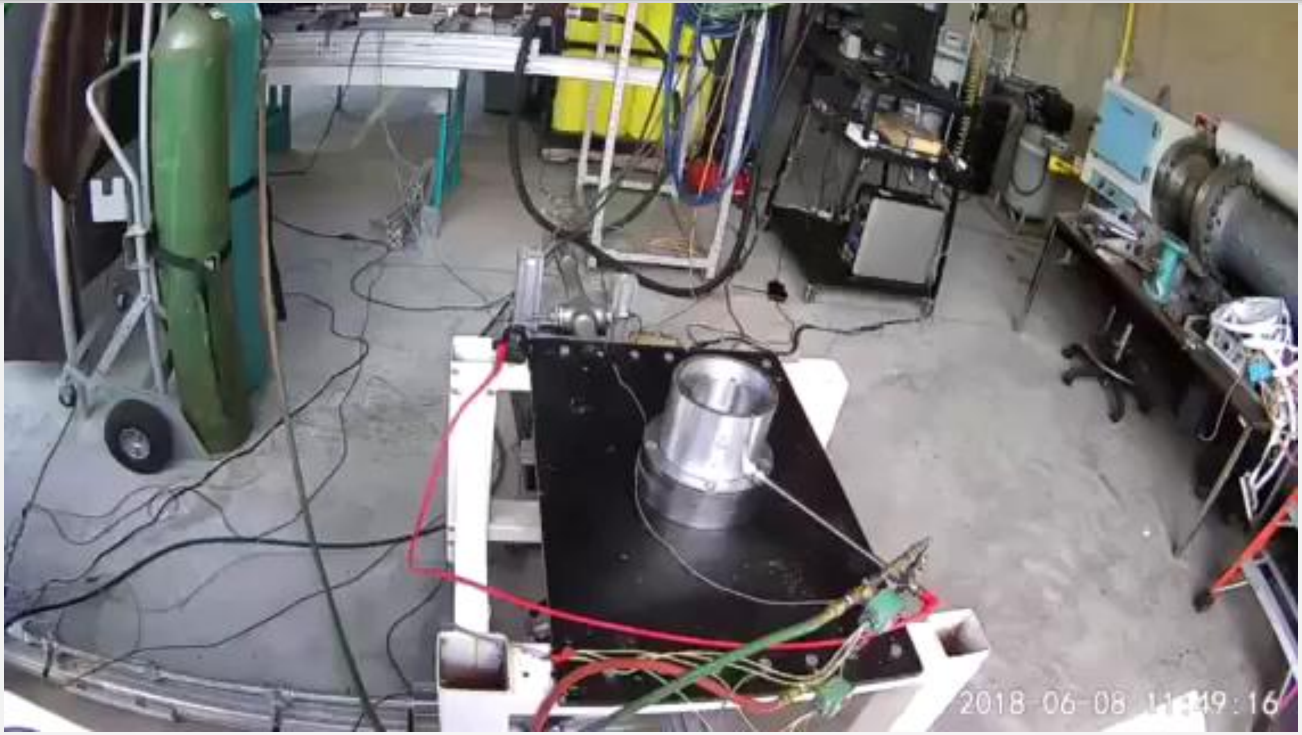


Flat for LAS

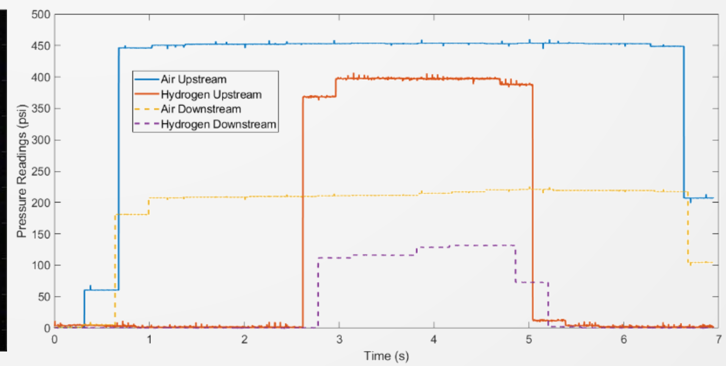
Simplified outer body to easily of create an operational map

Pre-Det

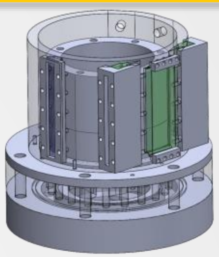
First Fire!

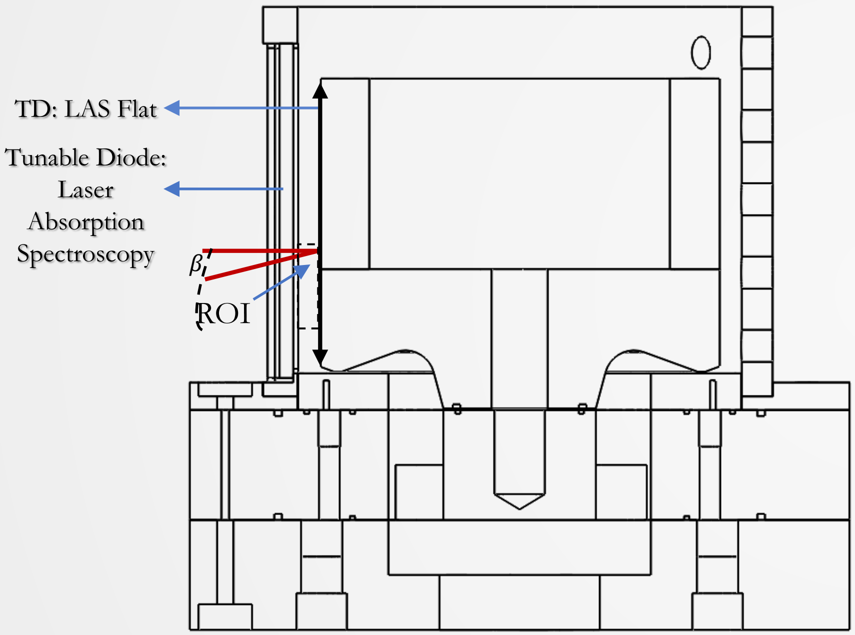


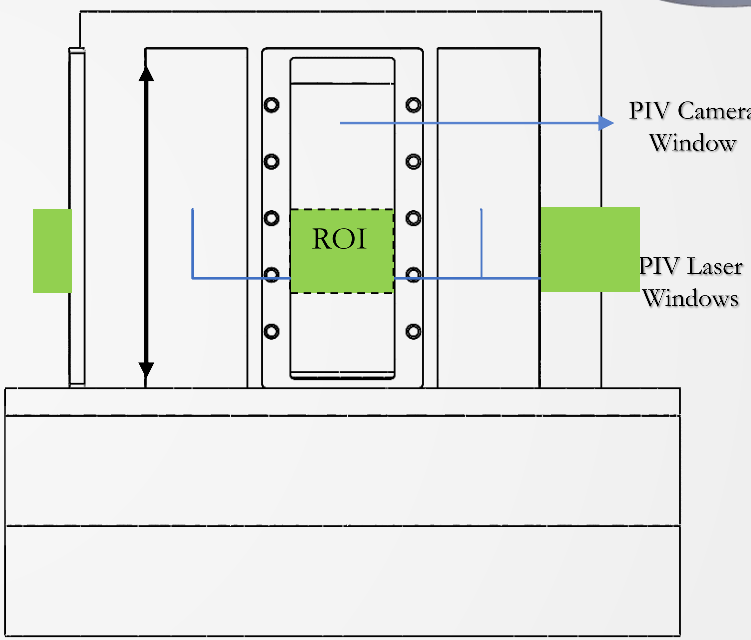
2 lbm, two detonation waves



PIV and LAS

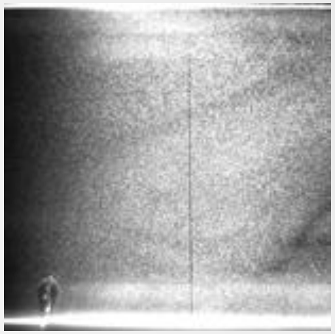




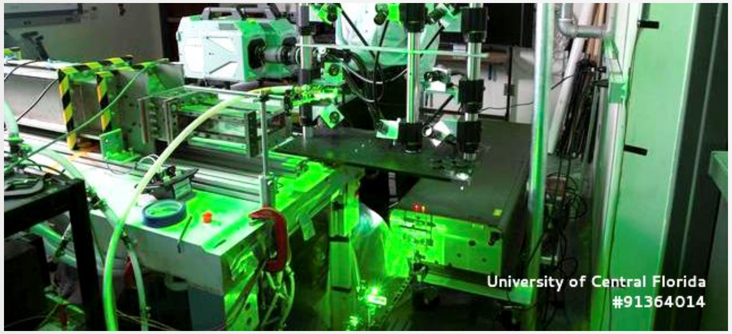


Both PIV and LAS are traversable axially

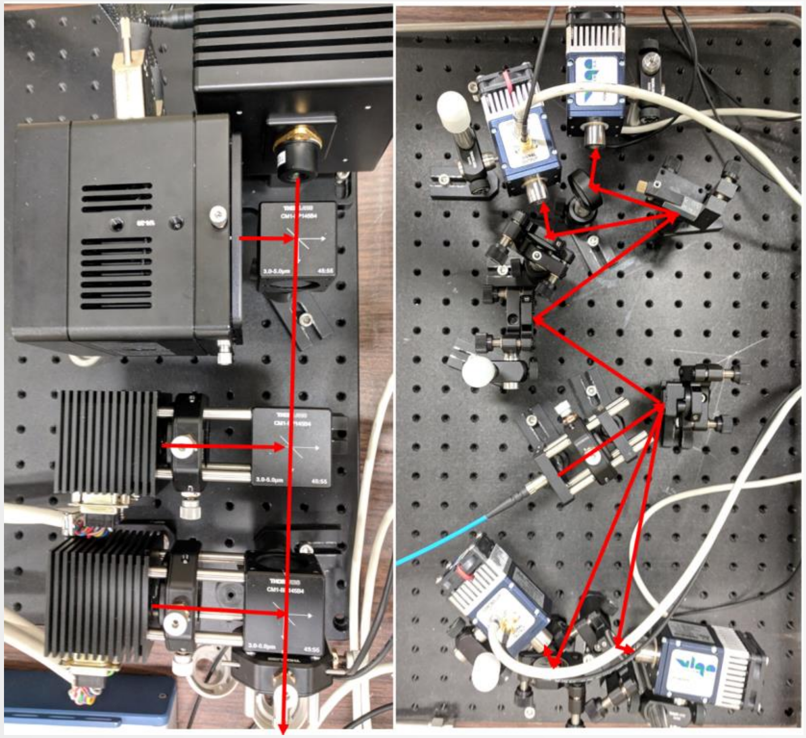
Advanced Optical Diagnostics



- High-speed PIV system (20kHz, 40kHz, 60kHz, 100kHz)
- High speed cameras 21,000-2,100,000 frames per second
- High-speed chemiluminescence CH*, OH* (40 kHz, 80kHz, 100kHz)
- Light-field focusing system for flow measurements and visualization
- LabVIEW control hardware and software
- Dynamic pressure transducers (PCB)
- Codes: DMD, POD, PIV, Physics-Based Models (Matlab/Fortran)



TD: LAS



Tunable Diode Laser Absorption Spectroscopy (TDLAS)

Two sub-systems:

The pitch (left):

Contains four lasers at different wavelengths.

$2.55\mu m$ and $2.48\mu m$ for water concentration and temperature.

$4.2\mu m$ for CO_2 concentration.

$4.7\mu m$ for CO concentration.

Each wavelength is multiplexed into a single beam and focused into a fiber cable.

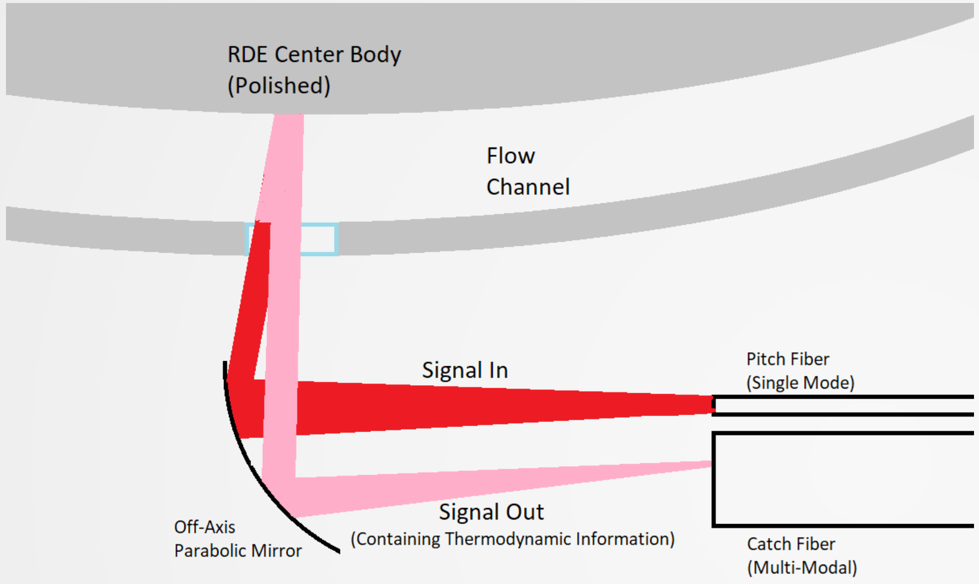
The catch (right):

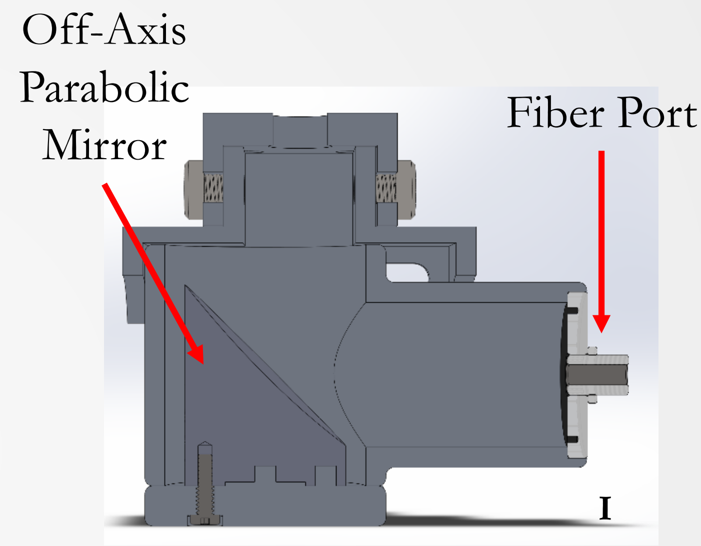
After passing through RDE combustion channel.

The four wavelengths are demultiplexed through diffraction gratings.

Signals measured with highly sensitive photovoltaic detectors.

TD: LAS





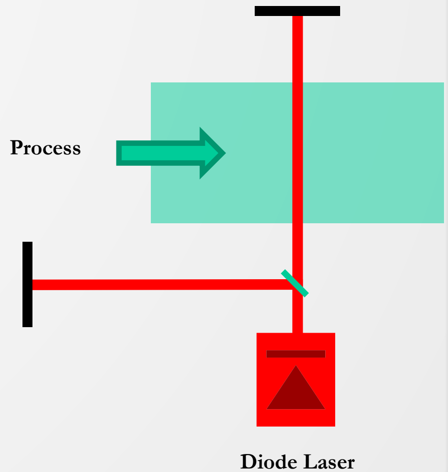
- **Beer-Lambert Law**

$$-\ln\left(\frac{I}{I_0}\right) = \sum_i \sum_j S_{ij}(T) X_j P L \phi_{ij}\left(\nu - \nu_{0_{ij}}\right)$$

$I = Transmitted\ Intensity \left(\frac{W}{cm^2 srHz}\right)$
$I_0 = Incident\ Intensity \left(\frac{W}{cm^2 srHz}\right)$
$S_{ij} = Linestrength \left(\frac{cm^{-2}}{atm}\right)$
$T = Static\ Temperature\ (\mathrm{K})$
$X_j = Mole\ Fraction$
$P = Static\ Pressure\ (atm)$
$L = Path\ Length\ (cm)$
$\phi_{ij} = Lineshape\ Function\ (cm)$

$\nu = Optical\ Frequency\ (Hz)$
$\nu_{0_{ij}} = Line\ Center\ Optical\ Frequency\ (Hz)$

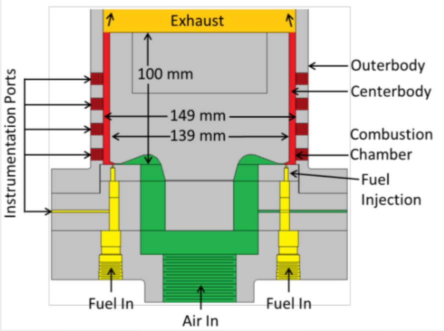
Subscripts
$i = Quantum\ Transition$
$j = Atomic/Molecular\ Species$

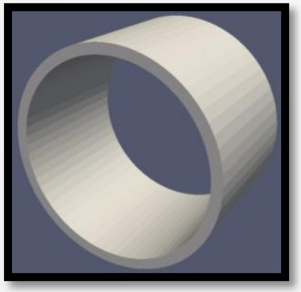


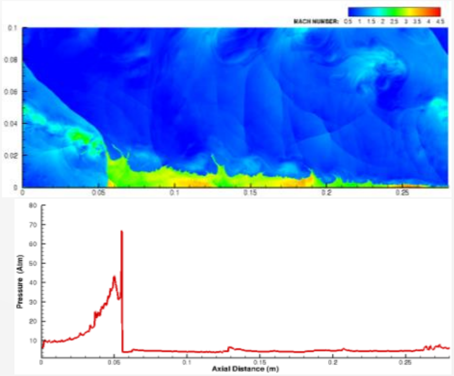
Computational Setup

Numerical Model and Challenges

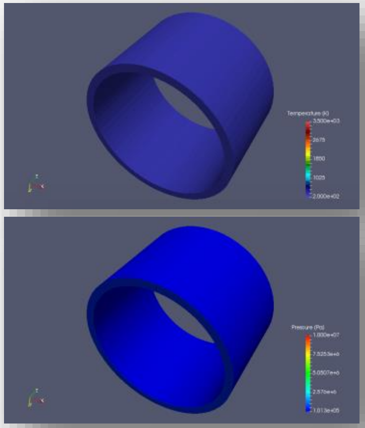
- LESLIE code - compressible LES solver with hybrid O(2)-O(3) central-HLLC scheme
  - Well established for detonation modeling under DTRA and AFRL effort
  - Time-accurate and parallel with two-phase capability operational
  - Initial grid ignores injectors: 3D grid 2160 x 500 x 40 cells used for simulations
  - Effusion BC in 2D (right) showed promise in 2D but failed in 3D to maintain mixture
  - Characteristic inflow BC implemented using inflow fixed stagnation temperature and pressure that allows inflow to shut down and restart based on local conditions







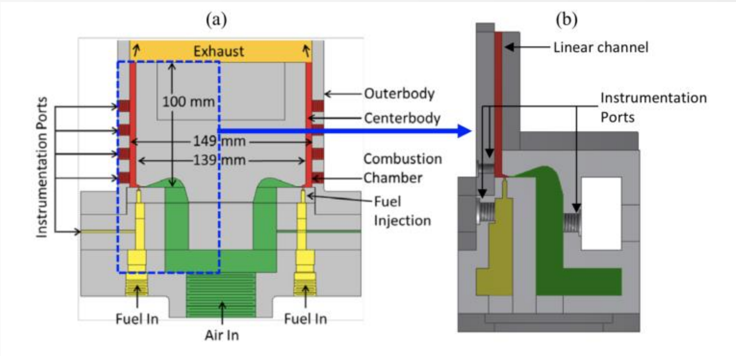
Successful sustained detonation in 2D setup

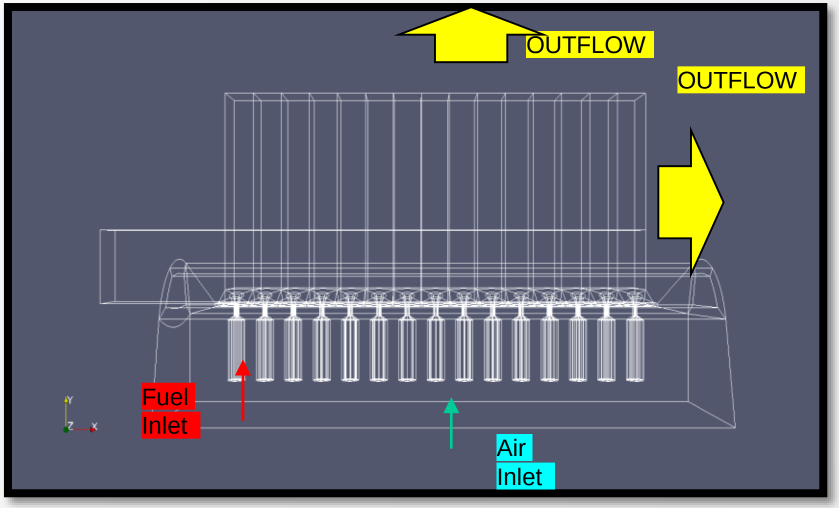


Successful sustained detonation for 1 cycle but failed in second cycles since mixture penetration was incorrect using the effusion BC.

Non-premixed injection system

- To evaluate the RDE inlet system a linear model based on NETL design is being modeled
- Full resolution of the injection assembly is being used here to understand the mixing process
- Such resolution in full 3D LES is impractical so assessment will be designed to modify the characteristic based BC to account for mixture variation
- This study will be non-reacting and focus only on mixing and assessing impendence based BC[2]





[2] P. Tudisco, R. Ranjan and S. Menon, 2018, "Simulation of Transverse Combustion Instability in a Multi-injector Combustor using the Time-domain Impedance Boundary Conditions", *Flow, Turbulence and Combustion* 101, pp. 55-76.

Summary and Future Plans

- Coal-RDE Facility has been setup and testing with seeded coal particles are under way
- 3D NETL/UCF rig has now been setup for simulations using LESLIE
  - Studies have been conducted to ensure grid quality and parallel performance
- Characterization of coal particle seeding: flowrate and stoichiometry
- Laser diagnostics implementation for pressure grain combustion and emissions measurements
- Evaluate mixing between air and fuel in an array of injectors as in the NETL/UCF rig focusing on non-premixed system to obtain impedance type BCs for 3D LES
- Two-phase LES is now being set up to study flames with coal mixtures