Effect of Mixture Concentration Inhomogeneity on Detonation Properties in Pressure Gain Combustors

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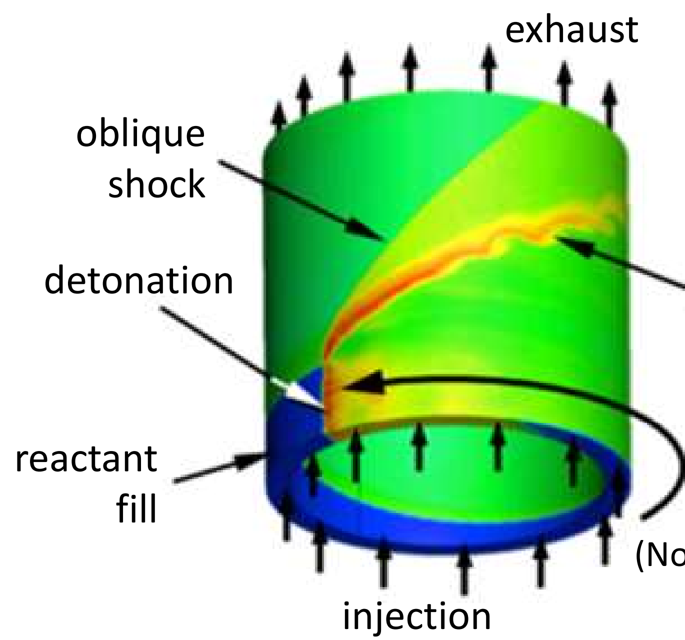
Pressure-gain combustion appeal and rotary detonation engines

Pressure gain combustion offers the potential of recovering and increasing the gas pressure lost in constant pressure combustion.

Gains in efficiency improvement have been estimated at potentially 5 to 10 percentage points, larger than most other single technological improvements (Idelchik, 2009)



(Nordeen, 2013)

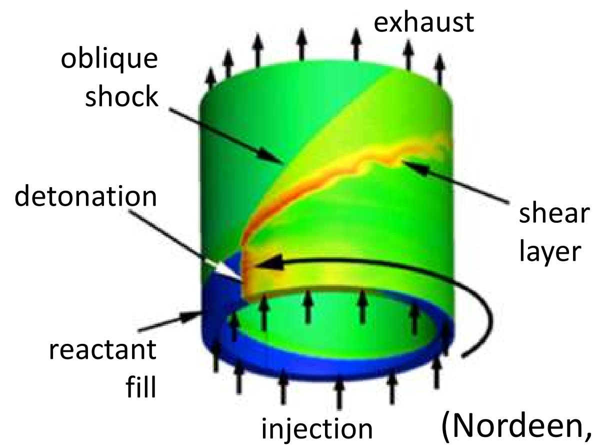
Rotary detonation engines are a particularly promising technology for integration in gas turbines for power generation. In a rotating detonation engine (RDE), the detonation propagates azimuthally around an annulus while fresh reactants are injected axially through the annulus .

Advantages include continuous injection of reactants and quasi-steady exit flow profile.

Rotary detonation engine issues and the importance of inhomogeneity

Although a promising technology, several key issues must be addressed before rotary detonation engines can be implemented for power generation, including:

1) Measuring and controlling CO and NOx emissions
2) Reactant injection and reducing reverse flow
3) High local heat fluxes within the combustor
4) Quantifying actual pressure gain
5) Fuel-oxidizer mixing
6) Detonation-mixture inhomogeneity interaction

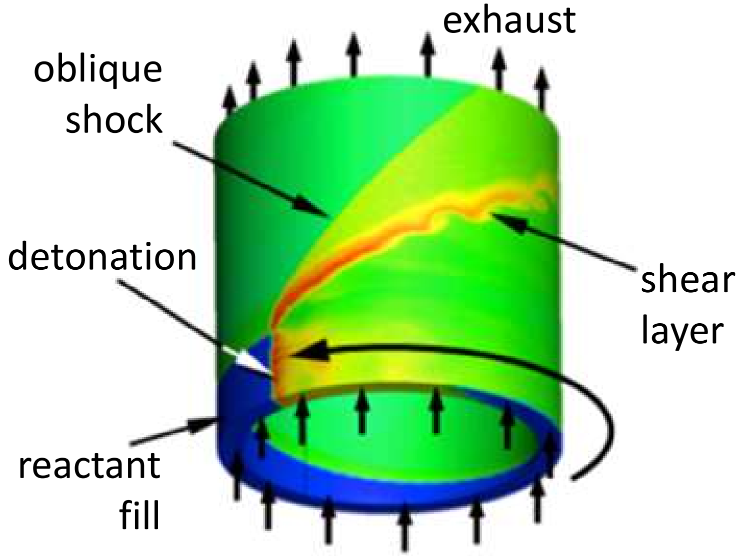


(Nordeen, 2013)

In a summary of the extensive RDE work completed at the Lavrent'ev Institute of Hydrodynamics, Bykovskii et al. (2006) concluded that "[t]he governing factor in obtaining an effective continuous detonation regime belongs to mixing in the region of transverse detonation wave propagation."

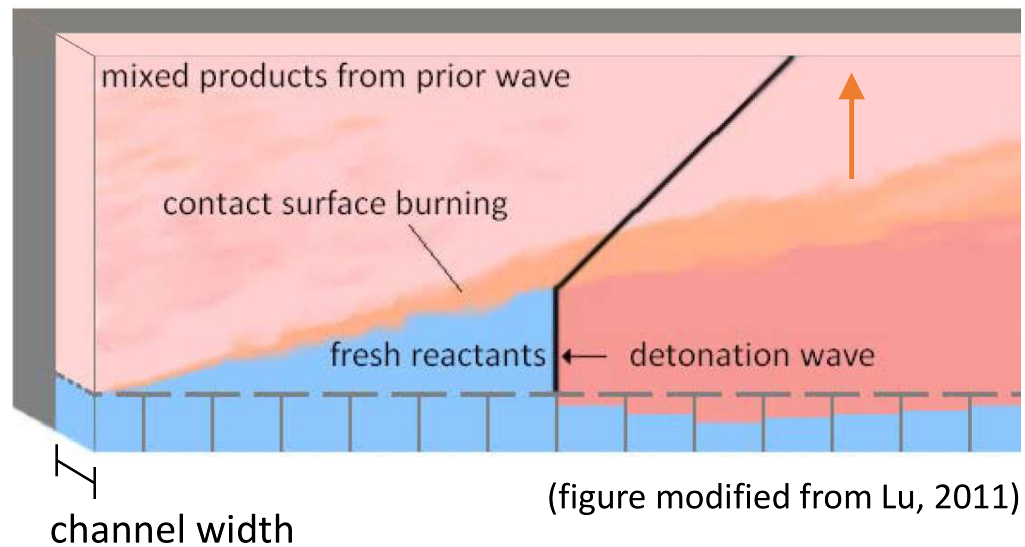
RDE schematics and geometric influences on mixing

RDE illustration



(Nordeen, 2013)

RDE flow schematic



(figure modified from Lu, 2011)

- RDEs are especially prone to spatial variations in mixture concentration due to:
  - Short mixing times (0.05 to 1 msec), since the combustor mixture region must refill before the detonation wave passes the injector holes again
  - Time-varying reactant flow rates due to changes in pressure downstream of the injection holes as the detonation wave passes

Project Objectives

In order to improve current rotary detonation engine designs to produce practical devices, the effect of concentration inhomogeneity on detonation properties will be determined.

The main objectives of this project are to:

1) determine the degree of fuel-oxidizer mixture concentration inhomogeneity in a rotary detonation engine

2) experimentally study the effects of inhomogeneity on detonation wave quality and stability (i.e., wave speed, planar vs non-planar, wave height, etc.)

3) perform a parametric study to better understand the relationships between combustor geometries and fuel/oxidizer injection.

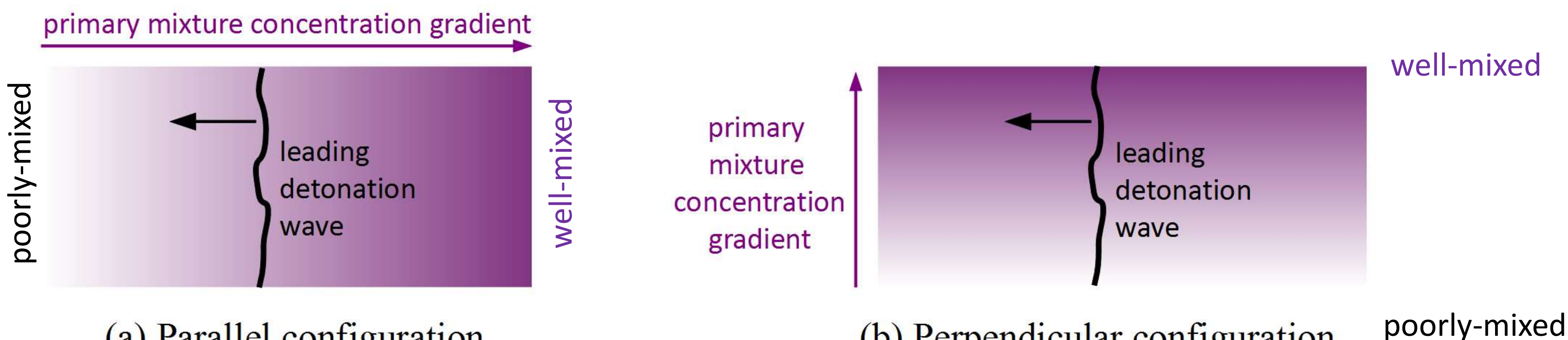
Project Tasks and Accomplishments – Year 1

Year 1 focused on the design, construction, and assembly of the test facility and initial testing with hydrogen-air mixtures:

1) The parallel and perpendicular test channels were designed and the parallel channel was machined and assembled.

2) Measurement systems and other ancillary systems were assembled and tested.

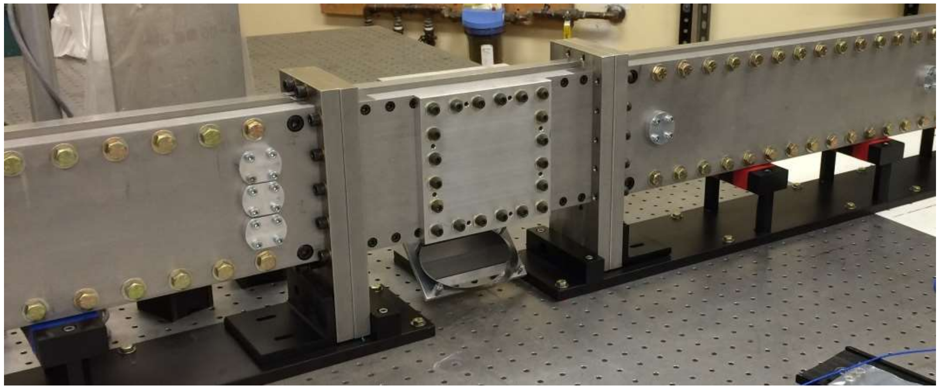
3) Detonation measurements in several quiescent mixtures were completed as an initial test of the system

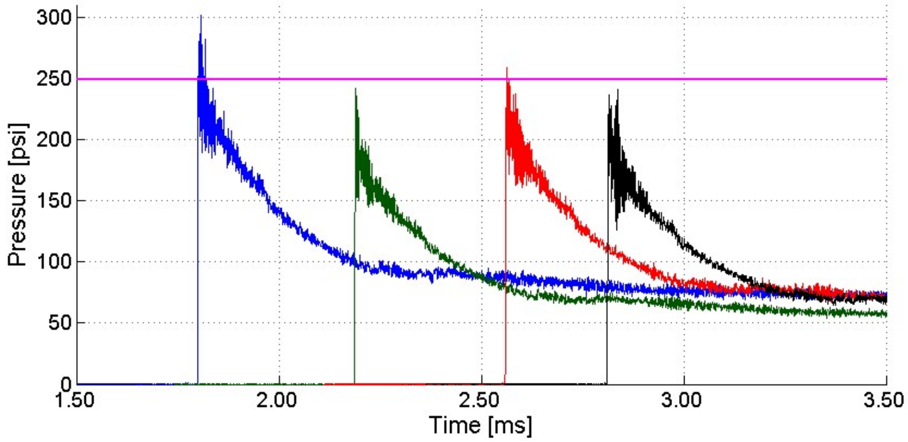


(a) Parallel configuration (b) Perpendicular configuration

Presentation Outline

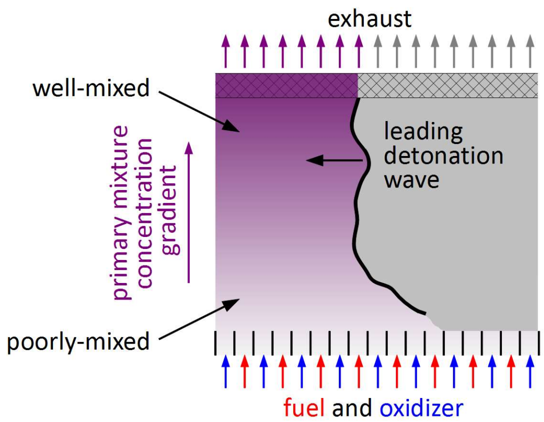
Design and fabrication of the facility



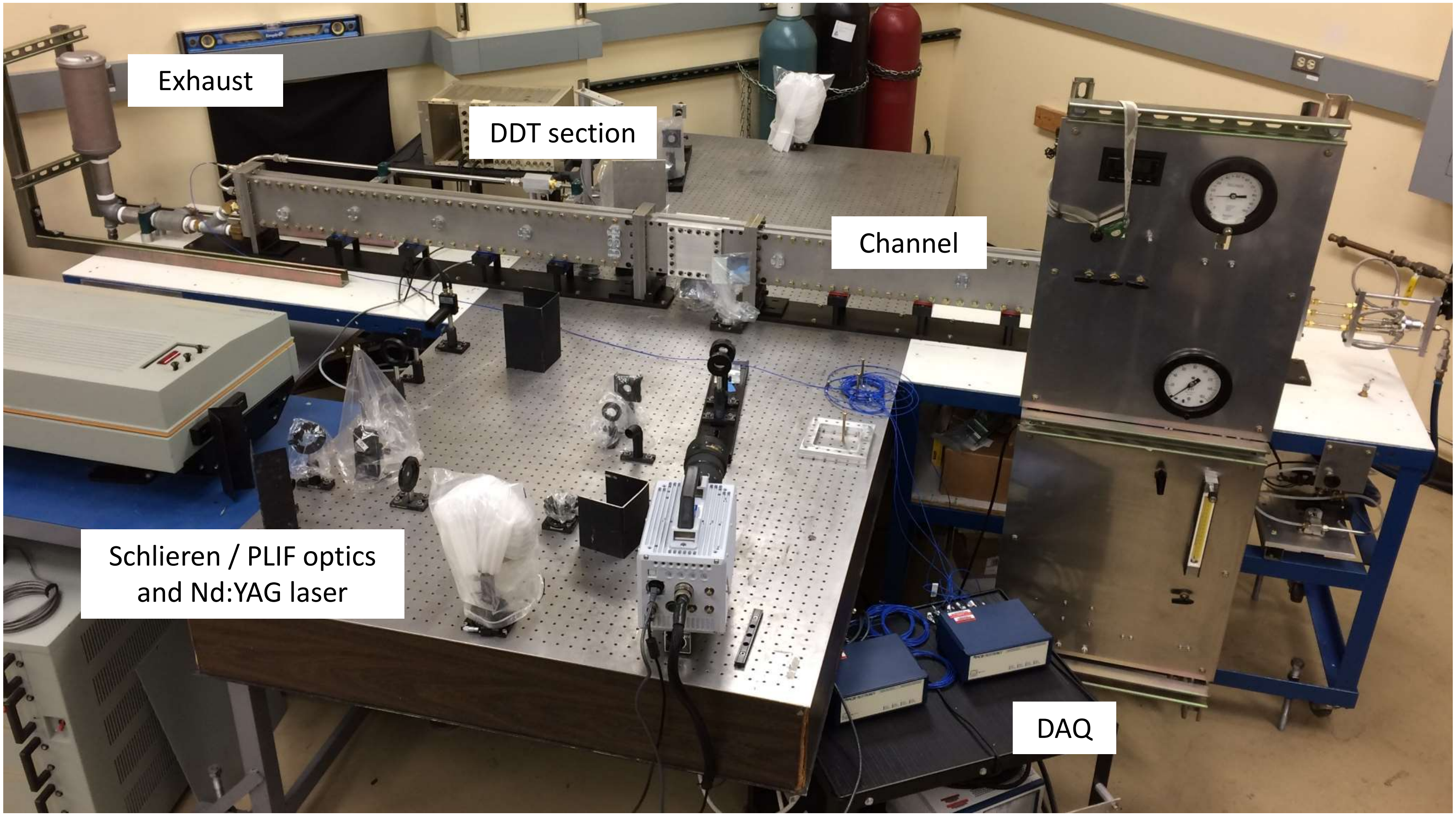


Preliminary testing – parallel configuration

Future work

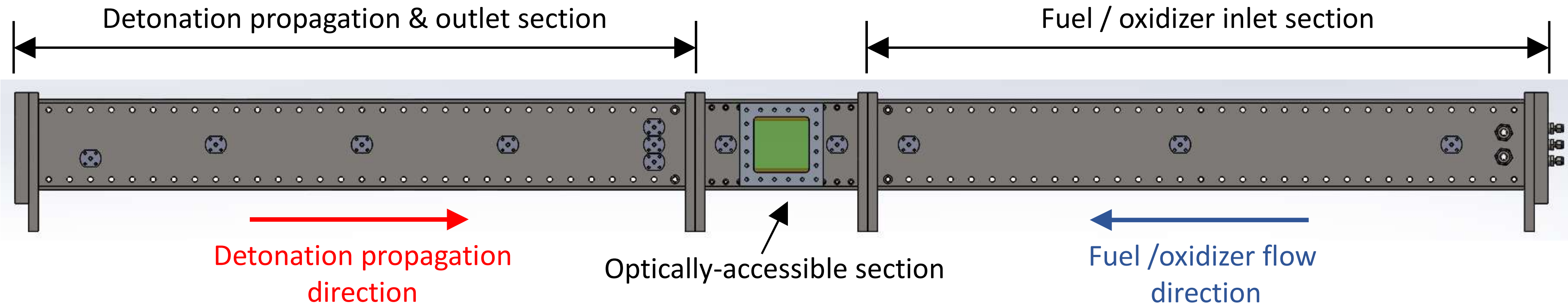


Overview of detonation facility

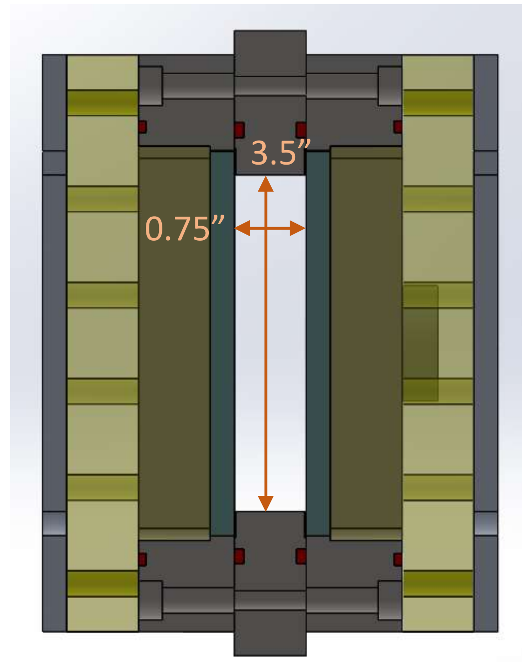


- Image shows all major components of the test facility
- Some components removed for clarity

Detonation channel description

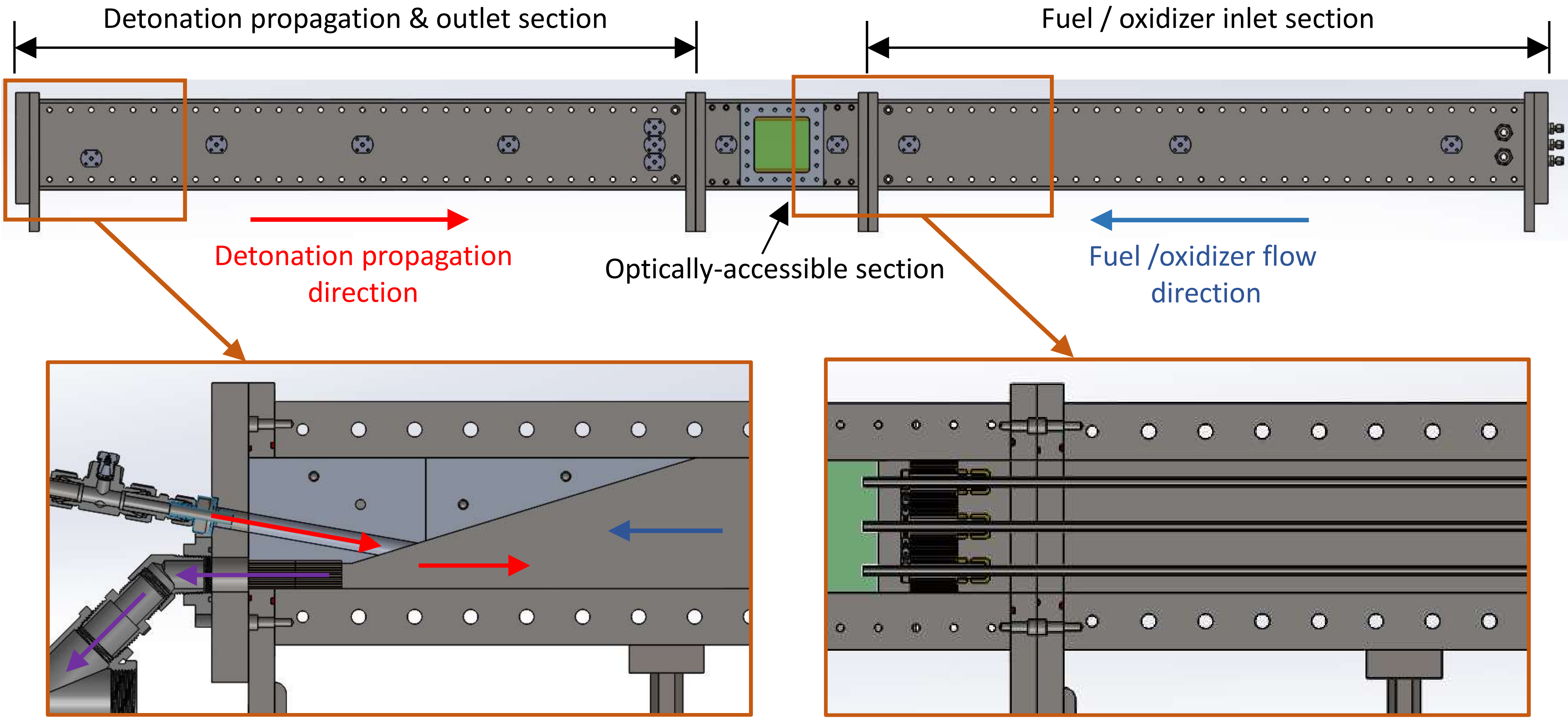


- Parallel test configuration shown
- Channel comprised of three main sections
- All sections bolted together to allow for geometry changes (no welds)
- Cross-section dimensions: 0.75” by 3.5”
- Overall length: ~10 ft.
- Sections are re-arranged to operate the test facility in different configurations



Optically-accessible section cross-section

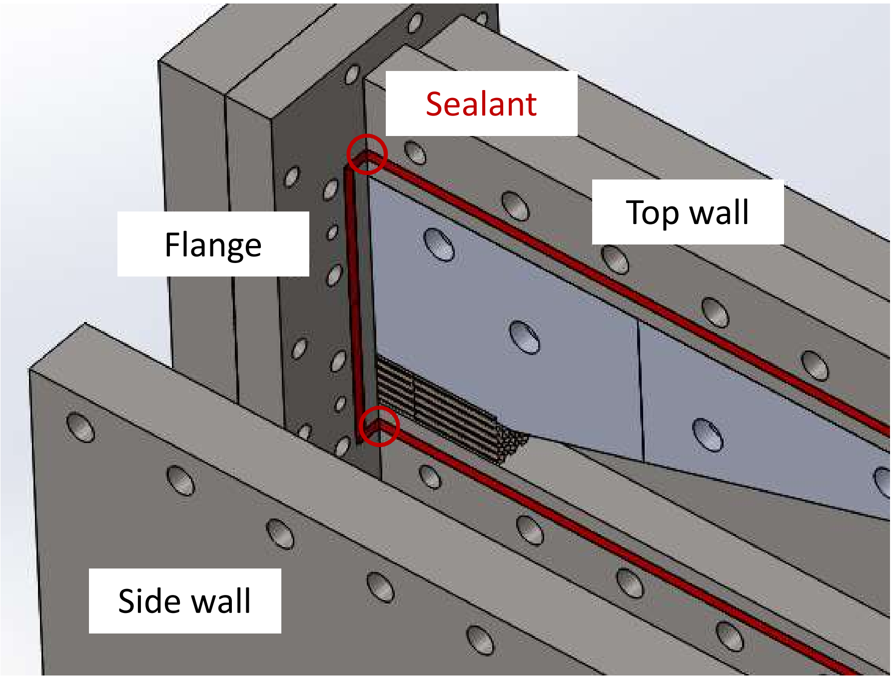
Detonation channel description

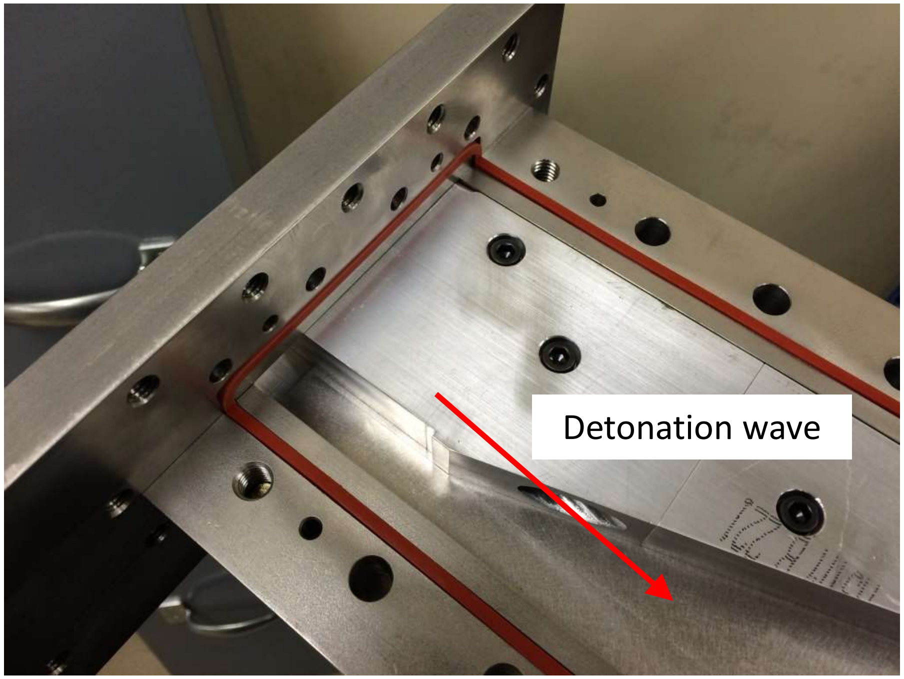


- Detonation initiated in DDT section
- Wave enters channel and expands along incline to prevent detonation wave failure
- Dilution air, water, and constrictions used to dampen detonation exiting combustor

- Location of fuel injection tubes is variable; allows for imagining of different parts of the fuel jet/air mixture without moving the optical window
- Channel can also be operated fully premixed

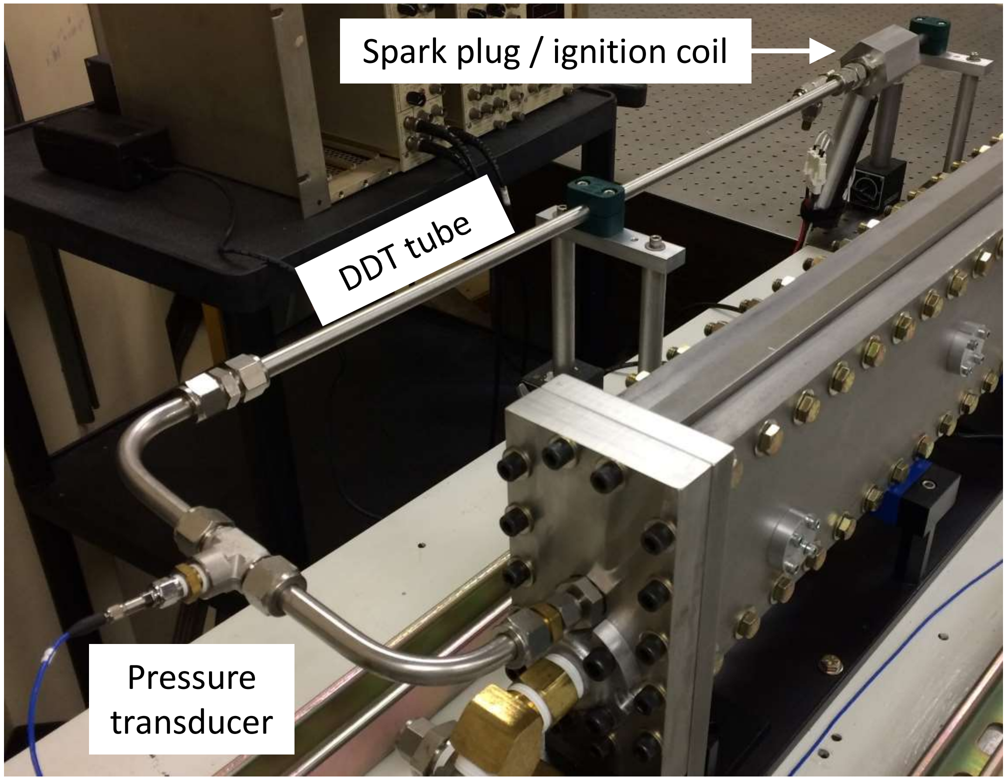
Channel wall sealing



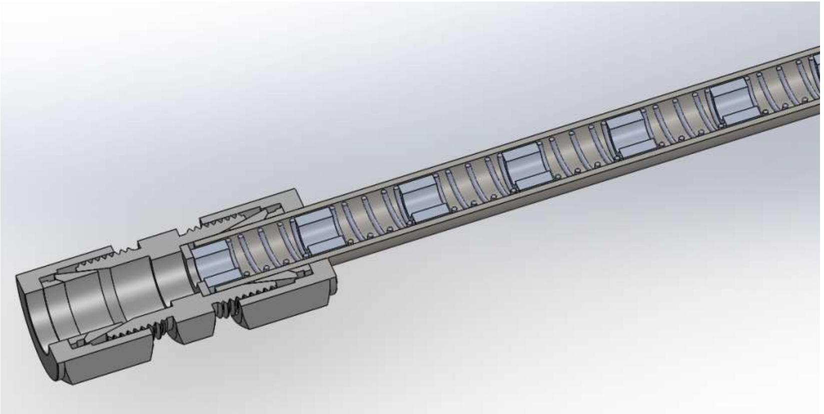


- All channel walls sealed with silicone o-rings and o-ring cord stock
- "3D" o-ring design – silicone sealant used to connect o-rings at flanges
- Allows for relatively easy modification of the channel

Deflagration-to-detonation transition section

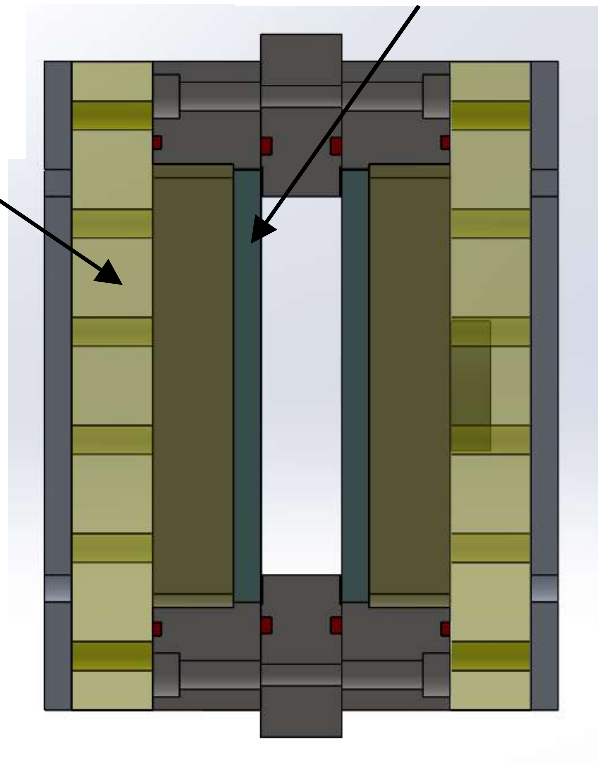


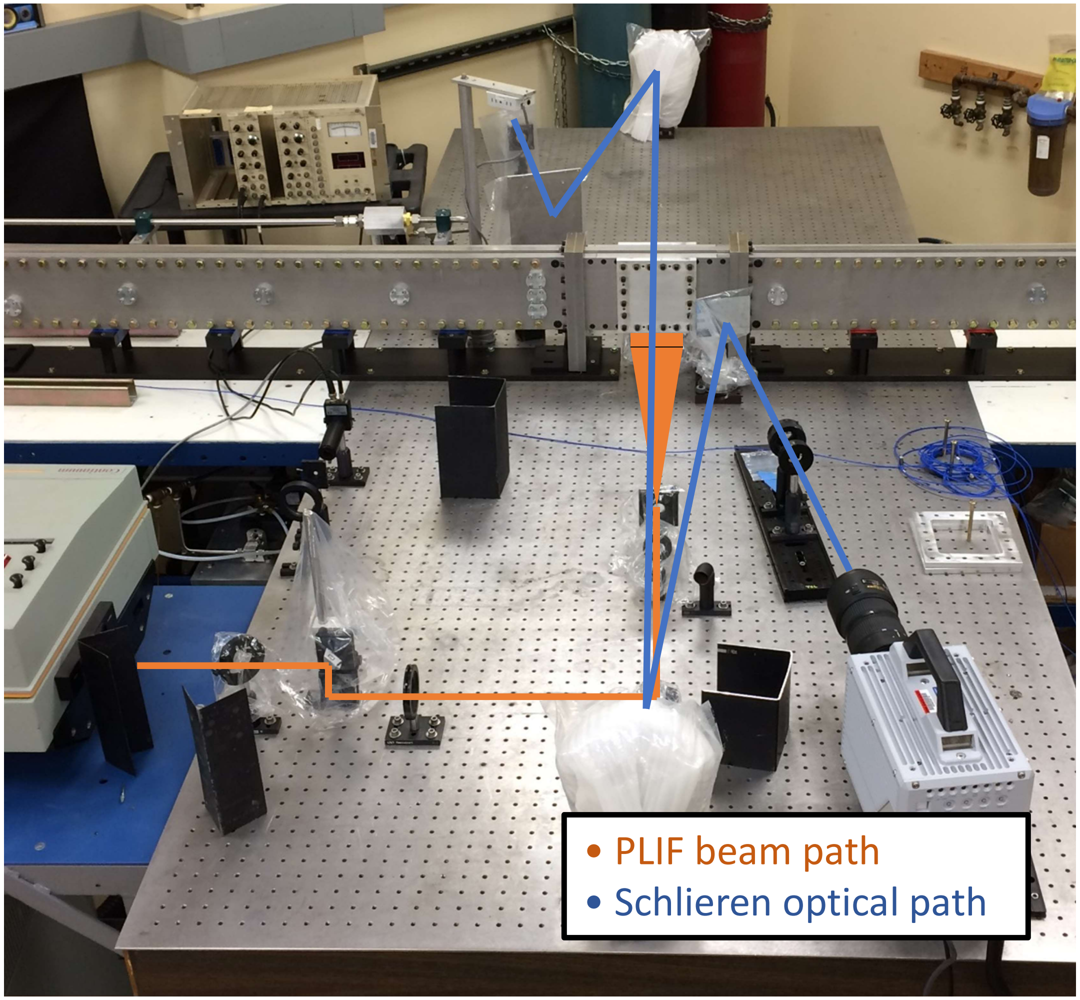
DDT tube cross-section



- O_2-H_2 mixture; spark plug (coil-on-plug type) ignition source
- 30" long DDT tube comprised of series of hollow cylinders (area reduction) and springs (hold spacing between cylinders)
- Pressure measured near tube exit

Optical access, schlieren, and PLIF systems





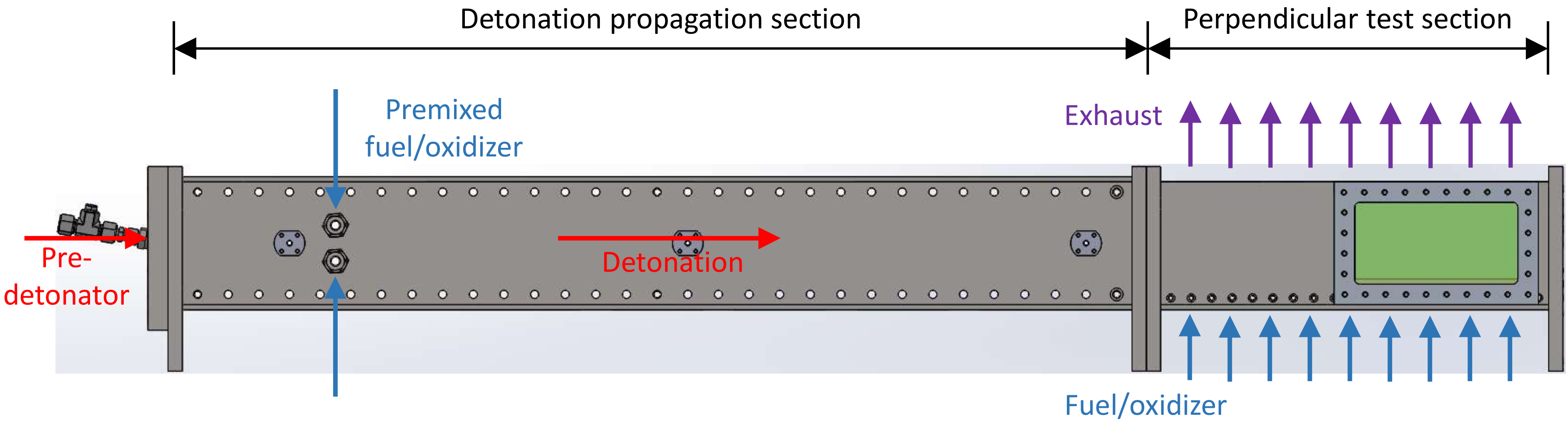
- Windows allow for complete optical access across the channel height
- Schlieren and PLIF optics aligned on single optics table

Operating conditions / Measurement techniques

Property	Range
Fuel composition	Hydrogen, blends of natural gas and hydrogen
Oxidizer composition	Air, oxygen, and oxygen-enriched air
Global equivalence ratio	Fuel lean through stoichiometric
Initial temperature	20 – 200°C
Initial pressure	1 – 4 atm

- In addition to the optical measurements described on the previous slide, the channel is instrumented with pressure transducers
  - 11 locations for pressure measurements
  - Velocities calculated from pressure measurements
  - Flush mounted with the inner channel wall
  - Used to trigger camera in schlieren system
- DAQ: 12 simultaneously sampled channels (2 to 4 MS/s/channel)

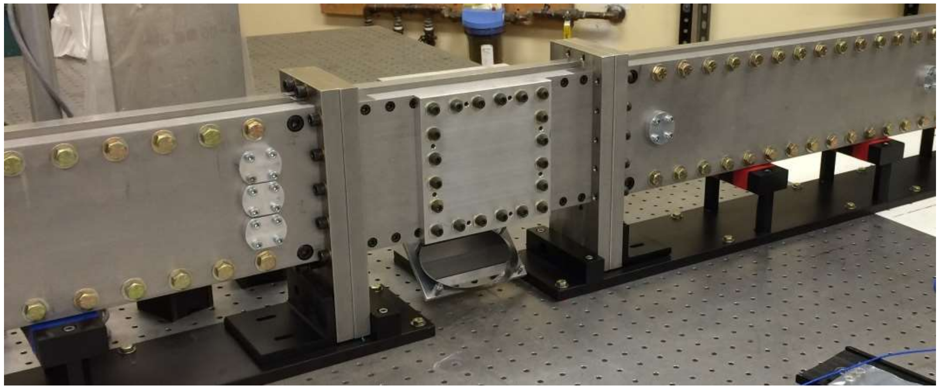
Perpendicular configuration (RDE simulation)

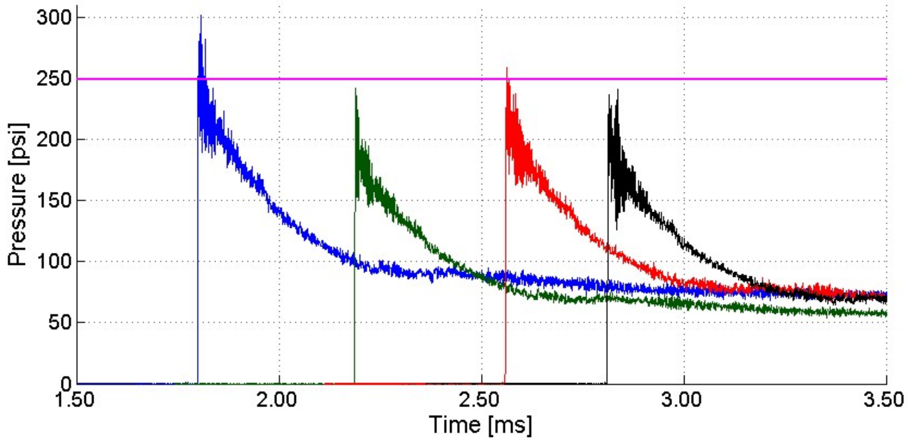


- Perpendicular test section is attached to part of the test channel to simulate an RDE
- Slow flow of fully premixed fuel/oxidizer used to establish planar detonation wave prior to interaction with the high velocity, perpendicular flow in the end section
- Gap width variable between 0.20 and 0.75 in. (discrete increments)

Presentation Outline

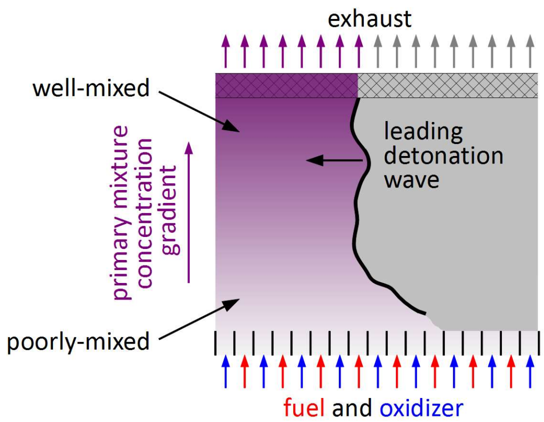
Design and fabrication of the facility



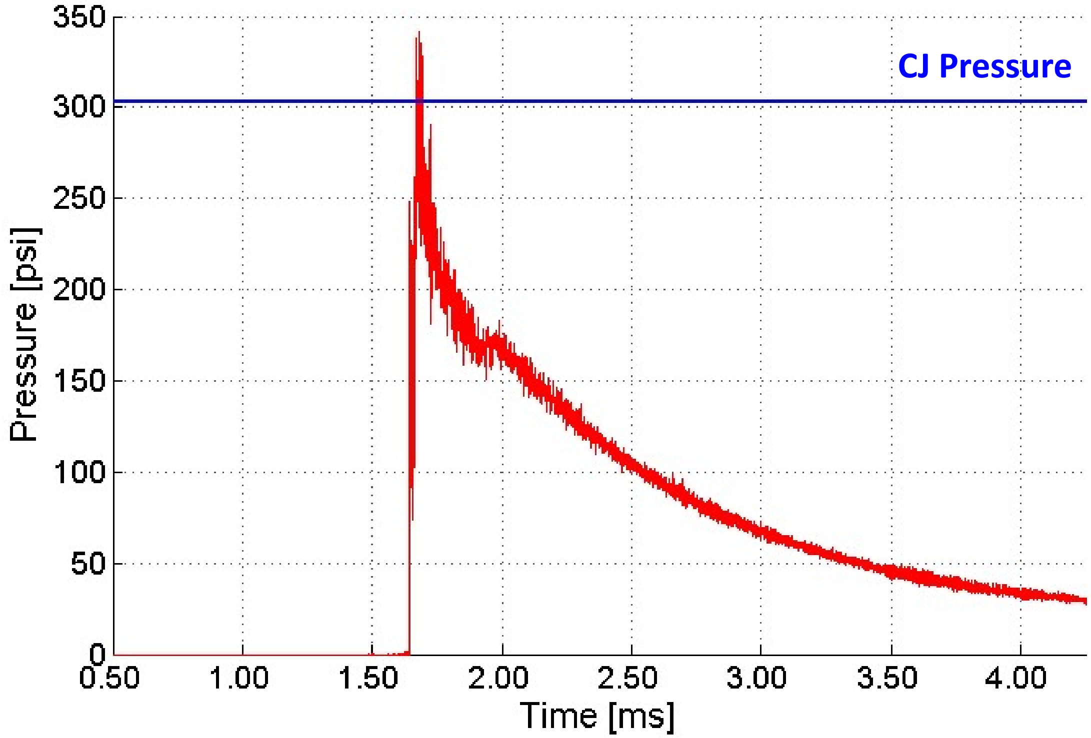


Preliminary testing – parallel configuration

Future work

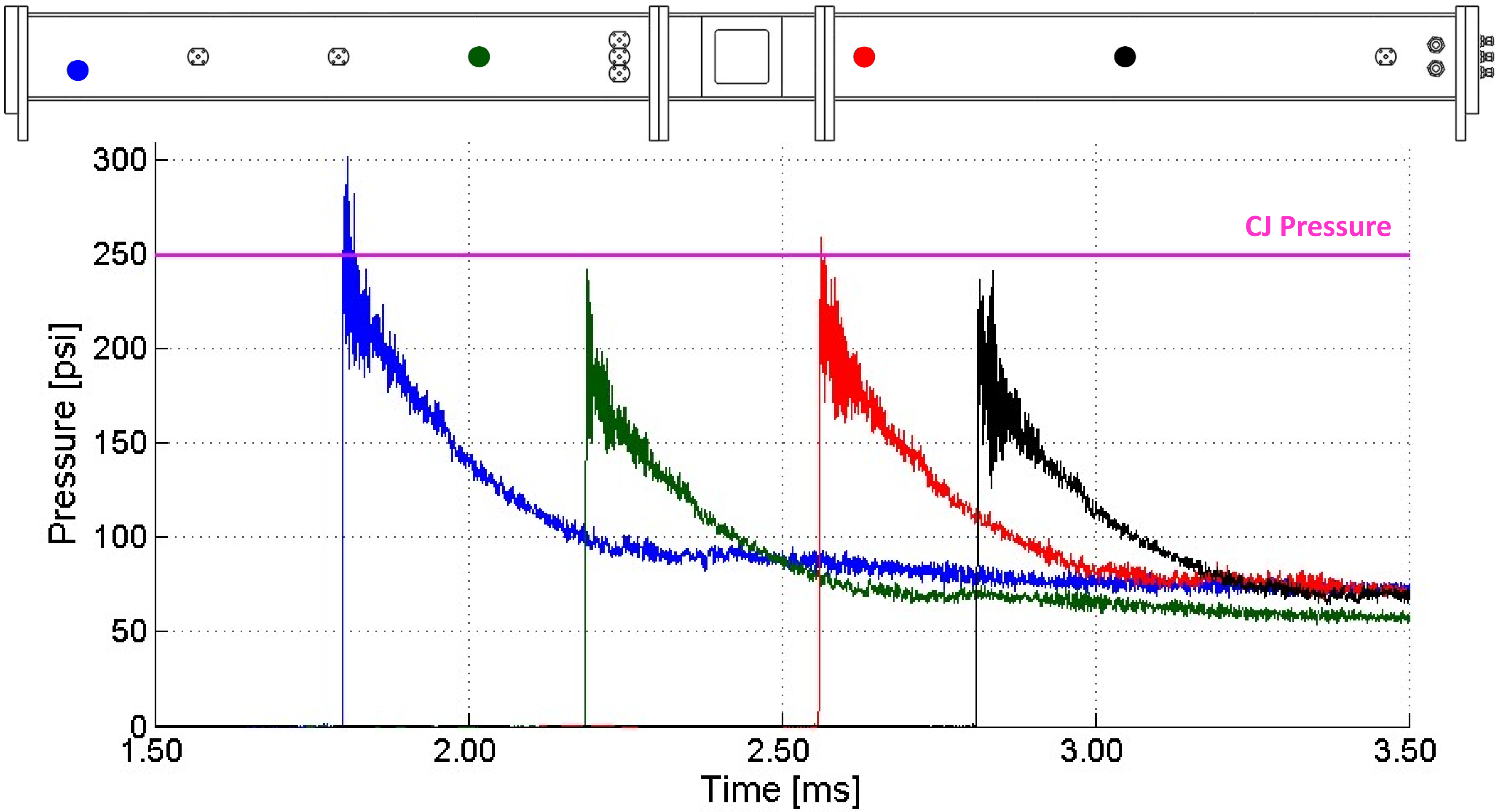


Deflagration-to-detonation section example pressure curve



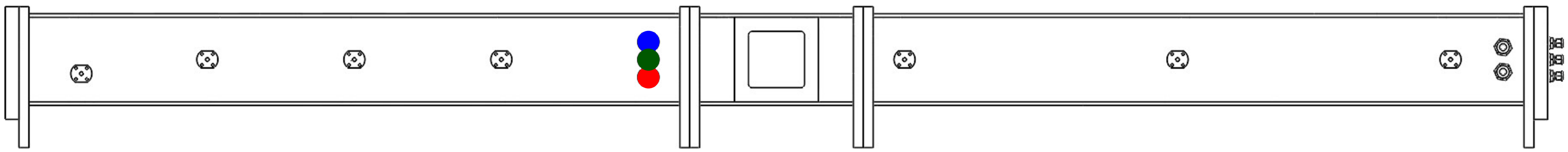
- Initial testing was completed with quiescent fully premixed H_2-air mixture in the channel
  - Premixed mixture produced using partial pressures
- Predetonator operated normally – stoichiometric mixture of H_2/O_2, 21°C, ~16.5 psia
- Figure demonstrates successful firing of predetonator device
  - Spark duration, spark gap width, and valve timing varied to achieve detonation

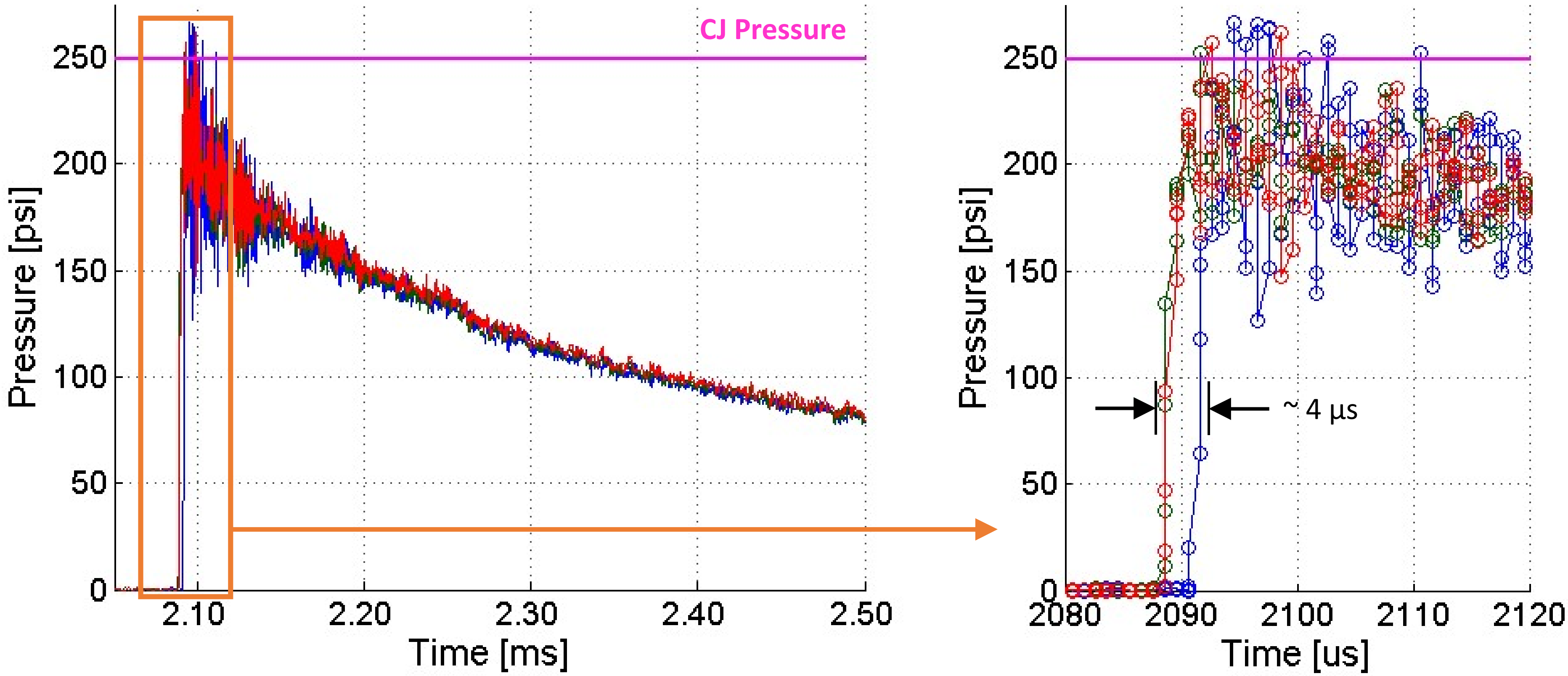
Example pressure profiles and detonation velocity calculation



- H_2-air stoichiometric mixture, 16.5 psia initial pressure, 21°C initial temperature
- Time delays calculated using a cross-correlation of the pressure signals
- Calculated velocity: 1921 m/s, ~2.5% below CJ velocity (1971 m/s)

Uniformity of detonation wave at exit of initiation section

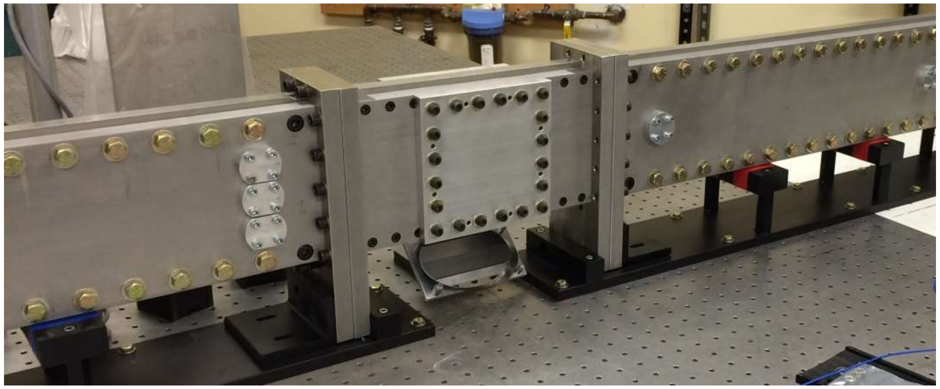


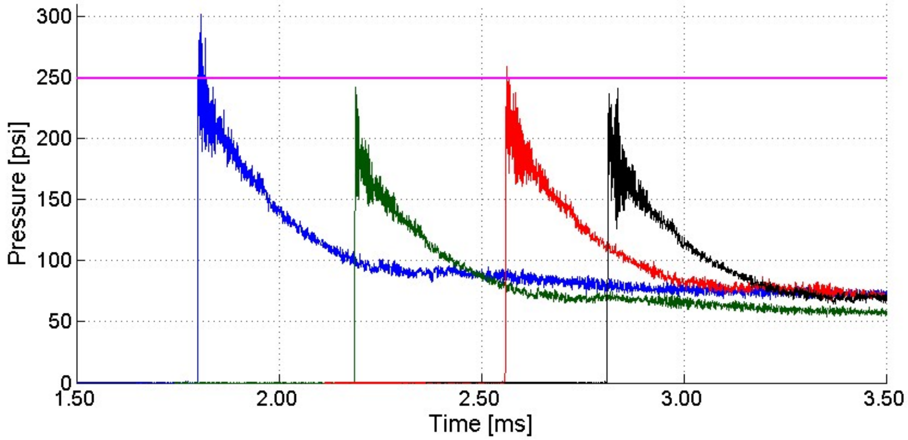


- Three PTs installed at same axial location to measure uniformity of detonation wave
- Leading detonation wave is uniform heading into window test section (~4 μs difference, approximately equal to the travel time across each PT face)

Presentation Outline

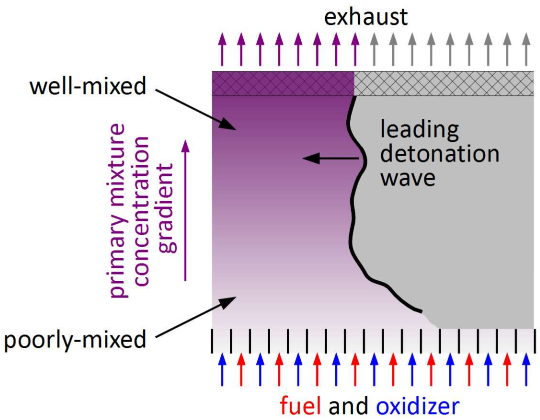
Design and fabrication of the facility





Preliminary testing – parallel configuration

Future work



Next steps

- The channel is fully assembled and has been tested with quiescent mixtures of H_2 and air
- Move the channel to a reinforced test cell by mid-November
  - Additional safety precaution for inhomogeneous mixture tests
- Start detonation measurements of inhomogeneous mixtures in the parallel test configuration
  - Measure mixture concentration variations with PLIF system
  - Schlieren imaging of detonation structures
- In addition, fully premixed detonation testing will be performed for comparison with mixtures with concentration variations

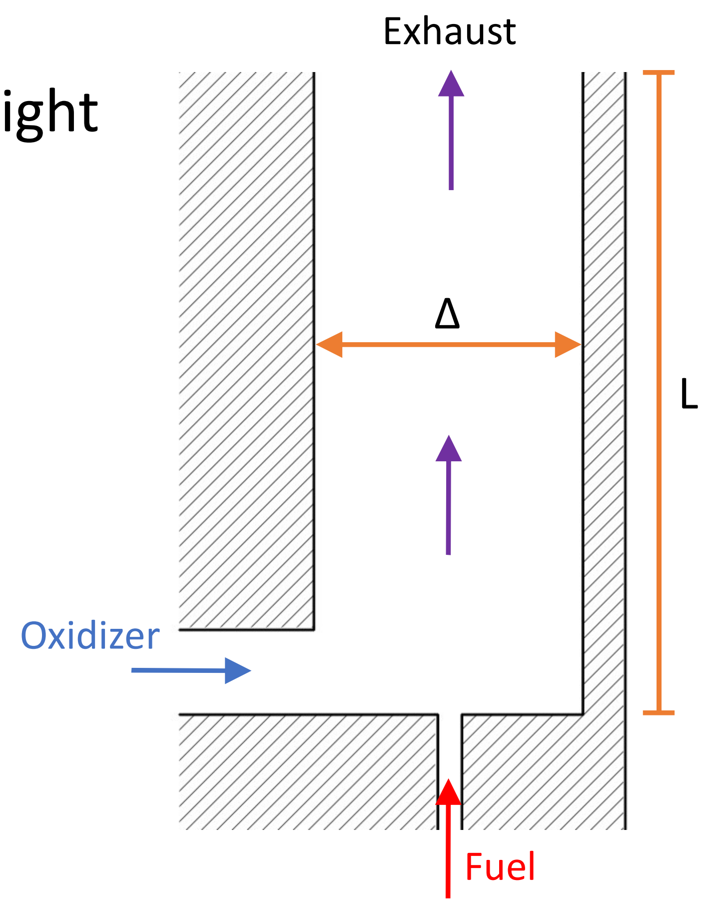
Additional tasks to be completed in Year 2

- In addition to parallel configuration detonation testing, measurements of the concentration variation in simulated RDE configurations is expected to begin next spring

- Will start with configuration shown on right
  - H_2 jets: round holes
  - Air jet: slot

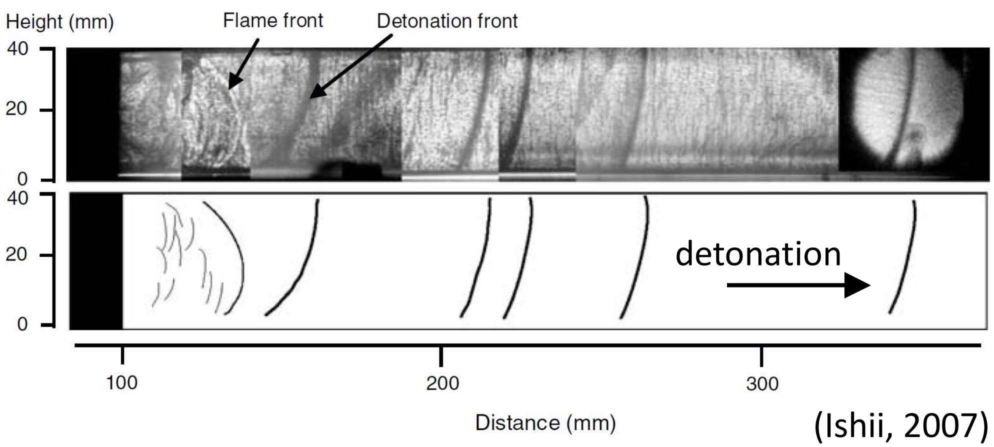
- Variable gap width, H_2 hole diameter, air slot width

- Perpendicular test section can be swapped out for testing of different geometries (H_2-air coflow configuration, for example)

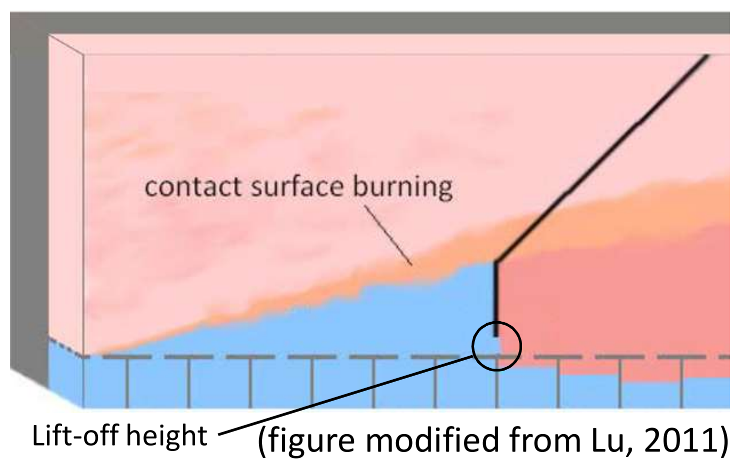


Future work / project goals

- Mixing conditions that result in leading wave separation from the reaction zone
- Effect of mixedness on detonation cell structure and propagation mode (stable, spinning, galloping waves)
  - affects detonation velocity and peak local pressures
- Measure leading wave front angle and detonation wave lift-off height above injection plane in a simulated RDE channel



(Ishii, 2007)



(figure modified from Lu, 2011)

Thank you!

Questions?

Project tasks – Year One

Task		Quarter											
		1	2	3	4	5	6	7	8	9	10	11	12
1.0	Project Management and Planning	●		●		●		●		●		●	
2.0	Design detonation channel and safety enclosure modifications	●	●										
3.0	Machining and setup of facility	●	●	●									
4.0	Determine the nature of detonation-inhomogeneity interaction in the *parallel* interaction configuration				●	●	●			●	●		
5.0	Determine the nature of detonation-inhomogeneity interaction in the *perpendicular* interaction configuration						●	●	●	●	●	●	●
6.0	Development of design guidelines and rules for detonation-inhomogeneity interaction										●	●	●
7.0	Reporting	●	●	●	●	●	●	●	●	●	●	●	●

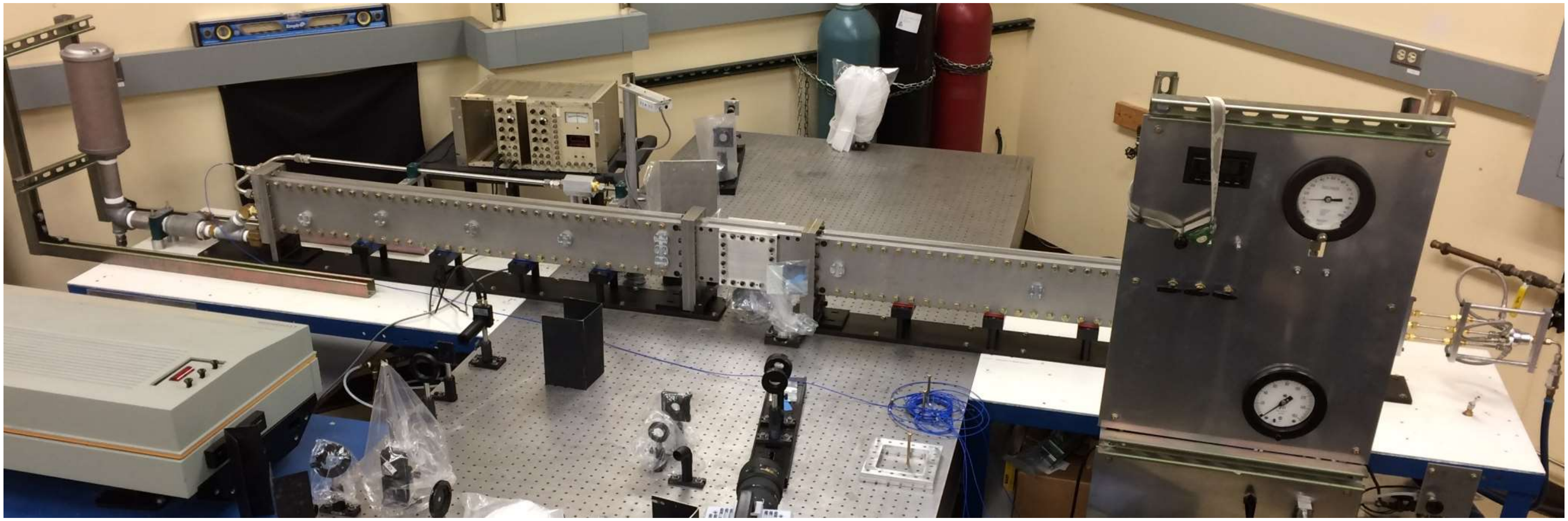
- Year 1: Design and build detonation channel modifications
  Test mixtures in the parallel configuration

Project tasks – Years 2 and 3

Task		Quarter											
		1	2	3	4	5	6	7	8	9	10	11	12
1.0	Project Management and Planning	●		●		●		●		●		●	
2.0	Design detonation channel and safety enclosure modifications	●	●										
3.0	Machining and setup of facility	●	●	●									
4.0	Determine the nature of detonation-inhomogeneity interaction in the *parallel* interaction configuration				●	●	●			●	●		
5.0	Determine the nature of detonation-inhomogeneity interaction in the *perpendicular* interaction configuration						●	●	●	●	●	●	●
6.0	Development of design guidelines and rules for detonation-inhomogeneity interaction										●	●	●
7.0	Reporting	●	●	●	●	●	●	●	●	●	●	●	●

- Year 2: Finish testing in the parallel configuration
  Test mixtures in the perpendicular configuration
- Year 3: Finish testing in the perpendicular configuration
  Elevated pressure and temperature testing
  Develop design guidelines and rules for detonation-inhomogeneity interaction

Thank you!



Project Objectives:

1) determine the degree of fuel-oxidizer mixture concentration inhomogeneity in a rotary detonation engine with a simple injector geometry widely used by the RDE experimental community fueled by hydrogen and hydrogen/natural gas blends with air

2) experimentally study the effects of inhomogeneity on detonation wave quality and stability (i.e., wave speed, planar vs non-planar, wave height, etc.)

3) perform a parametric study of combustor geometries and fuel/oxidizer injection.

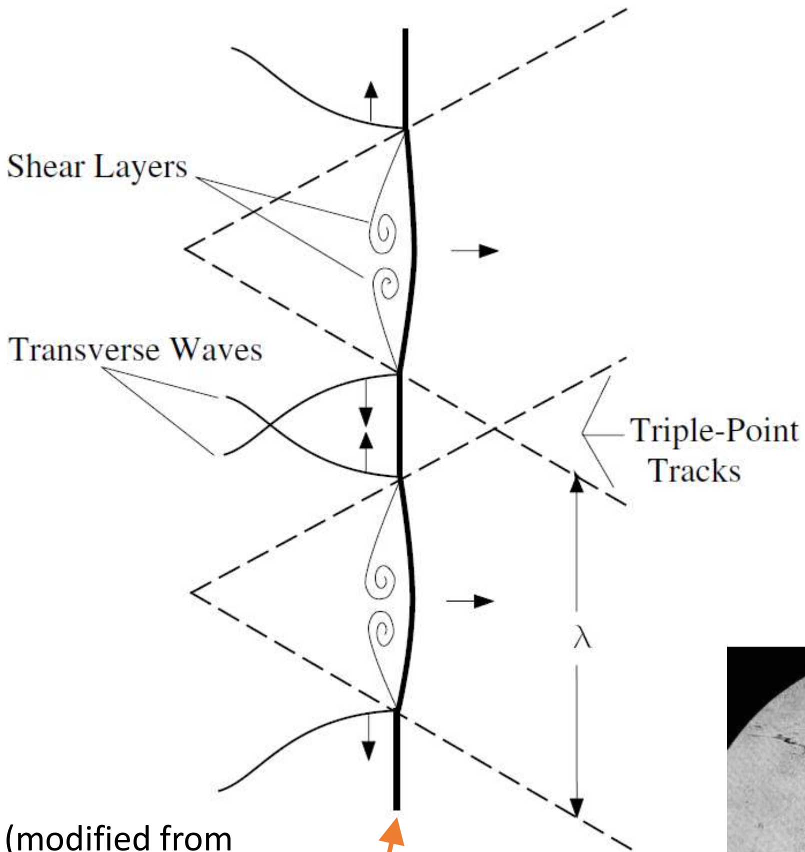
Extra slides

Previous studies on detonation-inhomogeneity interaction

Author	Year	Experimental or Numerical	Perpendicular or Parallel	Mixture	Description
Mikhalkin	1996	N	N/A	C_2H_4-O_2 CH_4-O_2	Regions of poorly mixed gases have a similar effect as inert diluents on detonation properties
Kuznetsov	1998	E	$=$	H_2-Air	Strong mixture concentration gradients dampen detonation propagation
Brophy	2006	E	$\perp$	C_2H_4-Air	Fuel distribution effects in a PDE
Bykovskii	2006	E	$\perp$	Various mixtures	Summary of RDE experiments highlighted the effects of poor mixing on operation
Ishii	2007	E	$\perp$	H_2-O_2 H_2-O_2-N_2	Deflection of detonation wave, skewing of cell structure and changes in detonation velocity
Kessler	2012	N	$=$	CH_4-Air	Shock wave-combustion zone decoupling led to turbulent deflagration
Ettner	2013	N	$\perp$	H_2-O_2	Concentration gradient effected on detonation cell shape, instability, and pressure distribution
Nordeen	2013	N	$\perp$	H_2-Air	Simulation of an RDE with variable mixedness
Driscoll	2015	N	N/A	H_2-Air	Simulation of mixing in a RDE

- Studies highlighted in red are discussed in further detail in later slides

Detonation propagation and cell structure

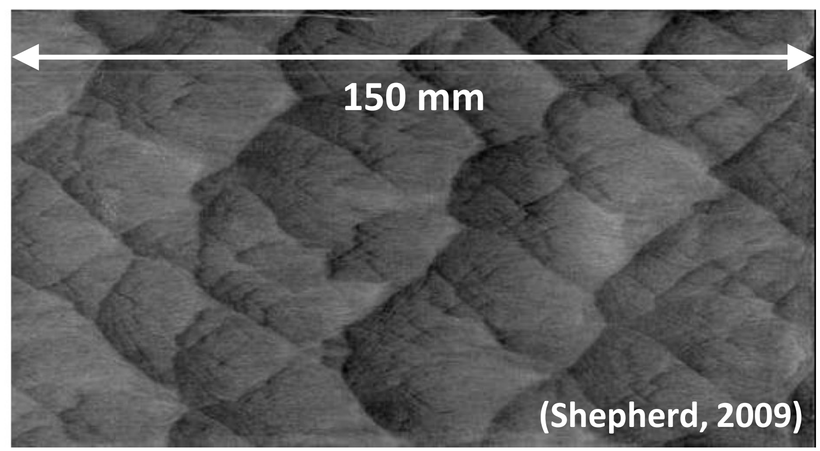


(modified from Austin, 2003)

Leading shock

1. Transverse shock waves travelling in opposite directions periodically collide, producing regions of high temperature and pressure
2. The leading shock is initially accelerated at the triple-point track interaction location, and then decelerates and weakens as the gas expands
3. This process repeats cyclically after another transverse wave interaction

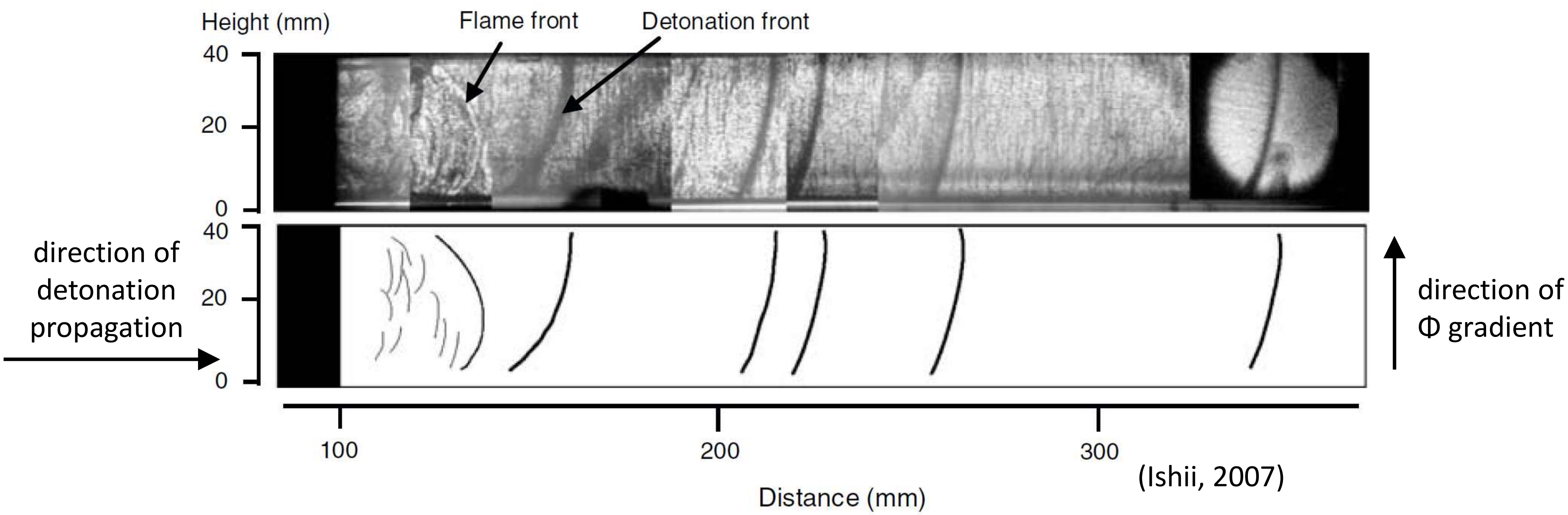
Shadowgraph ($2H_2$-O_2-$3N_2$)



Smoke foil record of triple-point tracks ($2H_2$-O_2-$2N_2$)

Previous studies on detonation-inhomogeneity interaction

- Majority of experimental studies relied on diffusion to produce concentration gradients



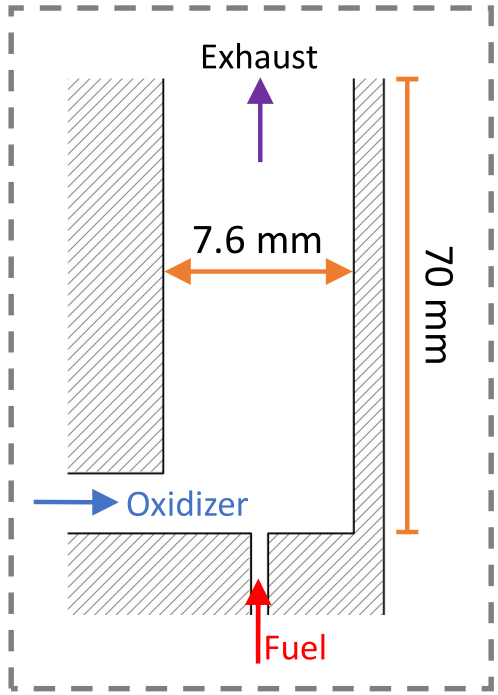
(Ishii, 2007)

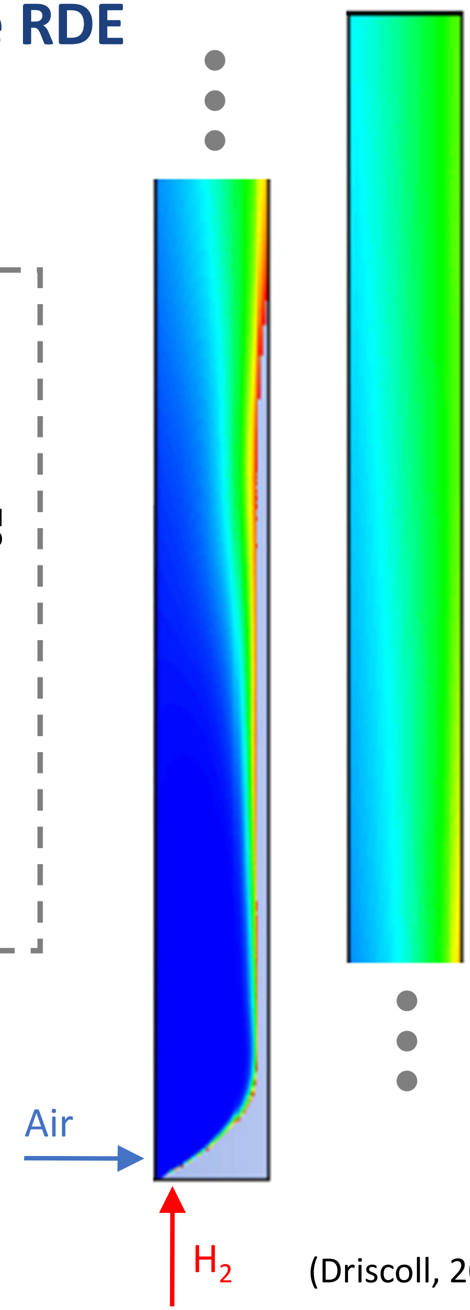
- For example, Ishii (2007) showed that concentration gradients can “skew” the leading detonation wave, resulting in irregular cell structures and a reduction in wave velocity

- Other studies have shown that inhomogeneity can result in shock waves decoupling from the combustion zone (resulting in turbulent deflagrations), a reduction or an increase in peak detonation pressure, and changes in mixture failure limits

Fuel-oxidizer mixing in an example RDE

- Simulation of H_2-air mixing in the Shank (2012) rotary detonation engine
- Authors found low fuel penetration into the air cross-flow near the injection location at baseline condition
- Air mass flux, fuel mass flux, and fuel injection location were varied





(Driscoll, 2015)

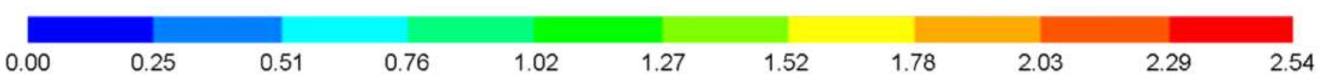
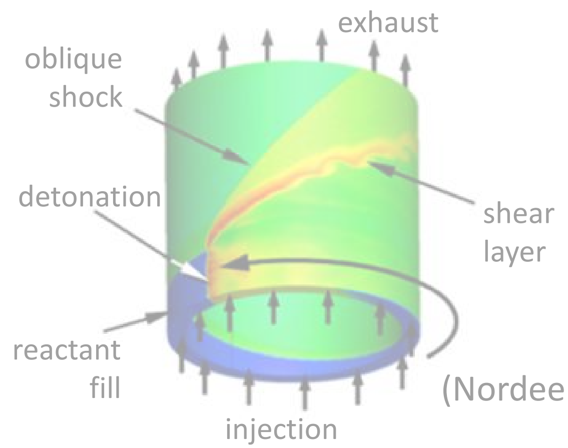


Figure 5: Contours of Equivalence Ratio for Case 1.00_1.0

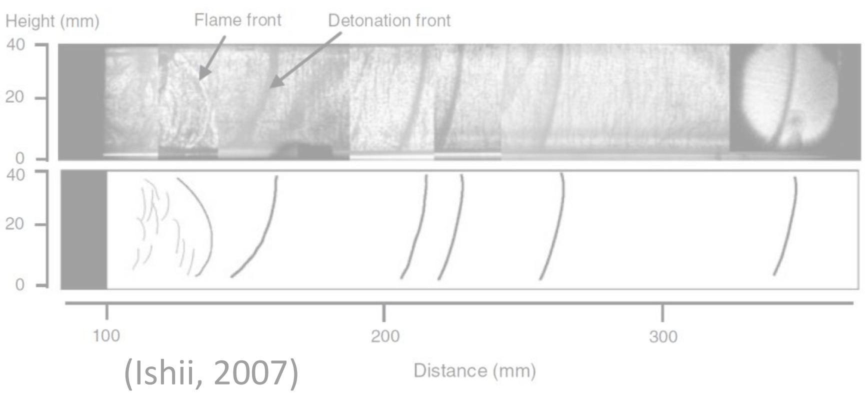
Technical Background

Typical rotary detonation engine configurations



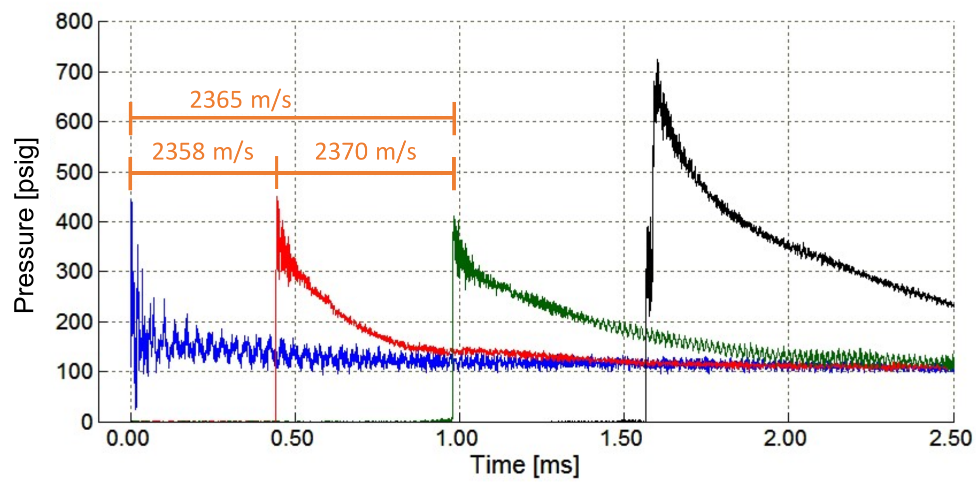
(Nordeen, 2013)

Previous studies of detonation-inhomogeneity interaction

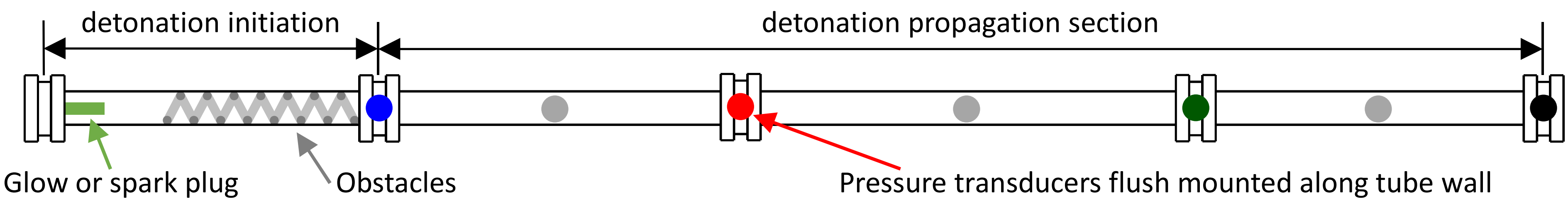


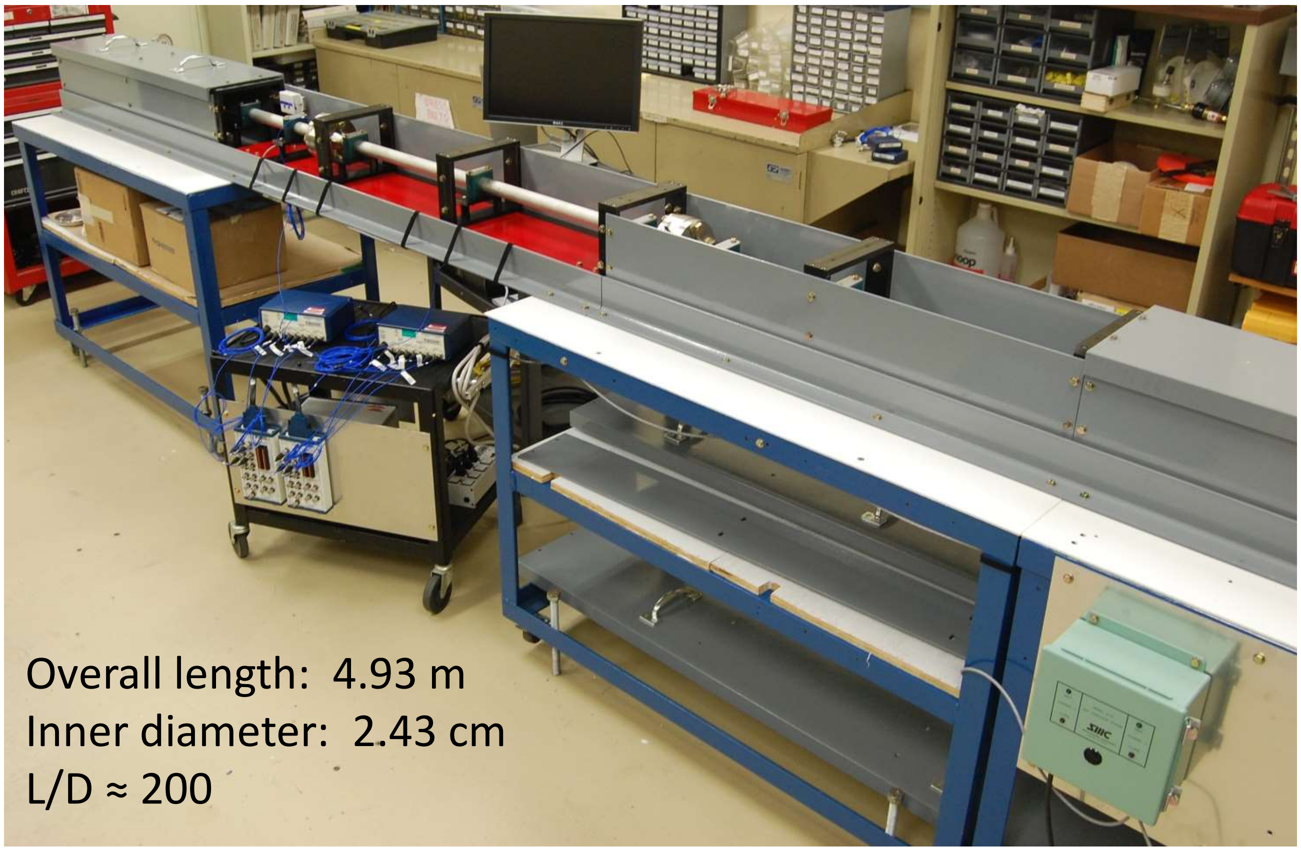
(Ishii, 2007)

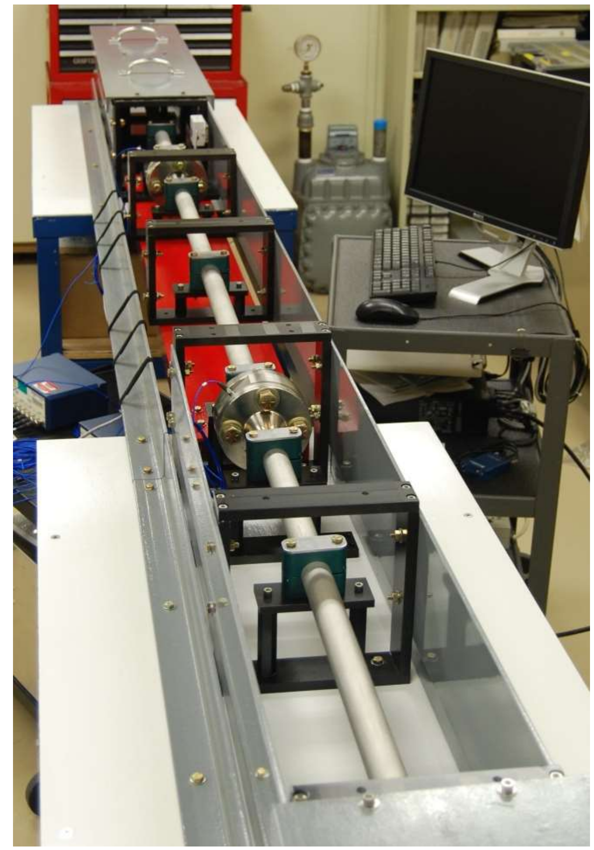
Penn State's detonation tube facility and other gaseous detonation work



Confined channel – detonation interaction study facility

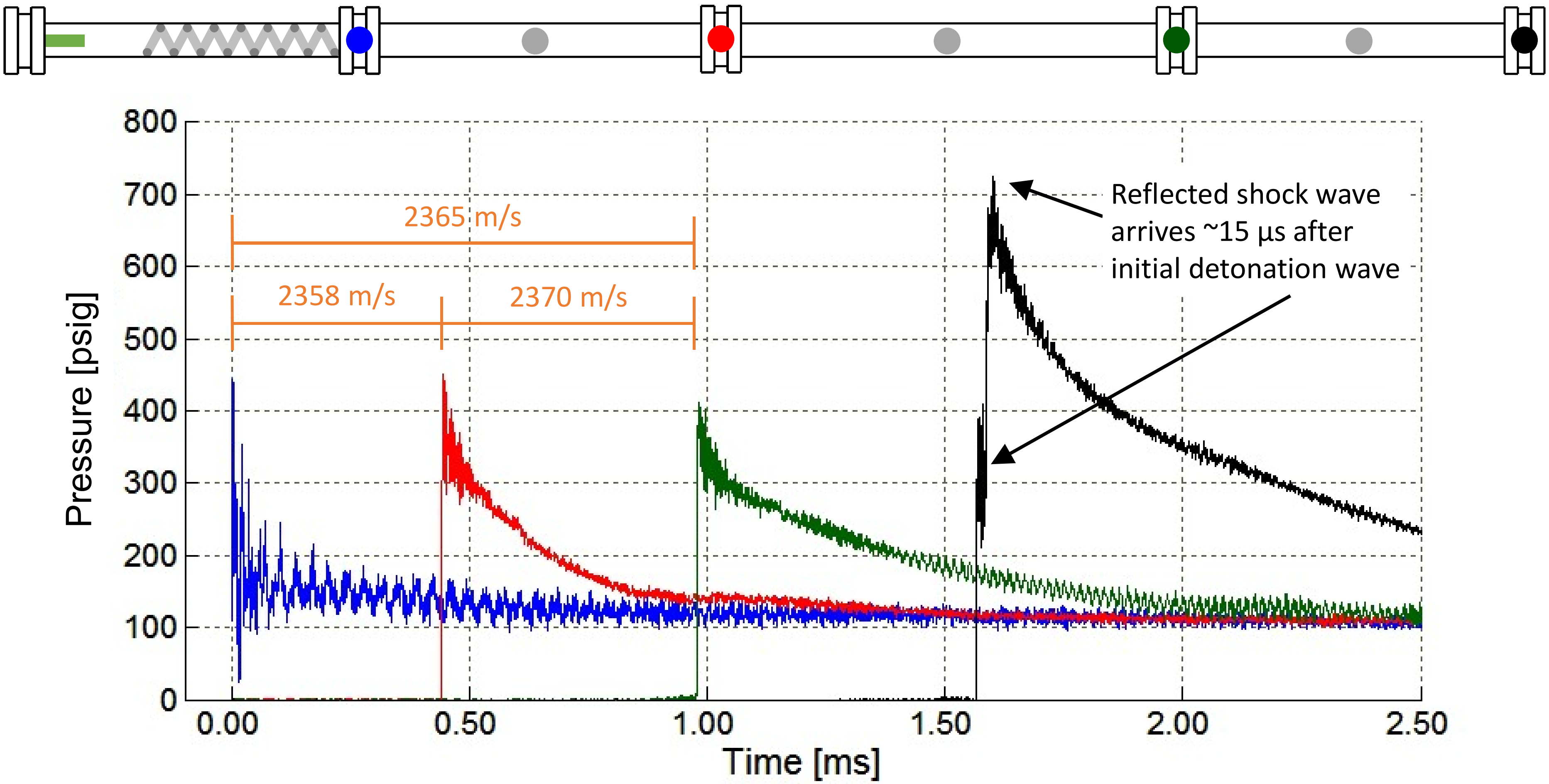






Vacuum system, gas mixing/delivery system, etc. not shown

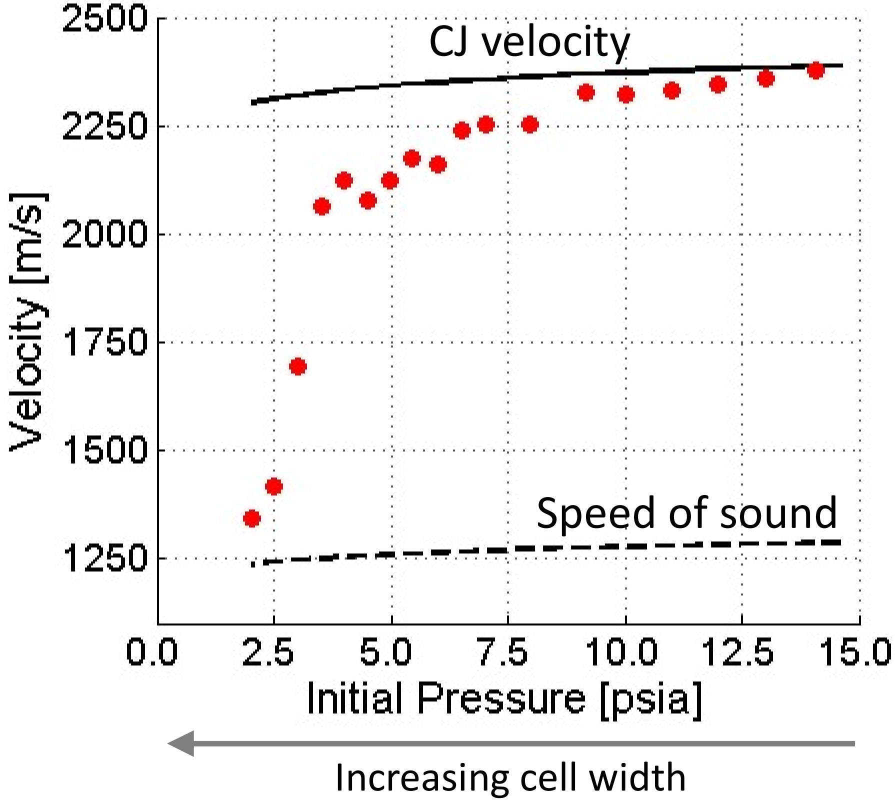
Example pressure profiles and detonation velocity calculation



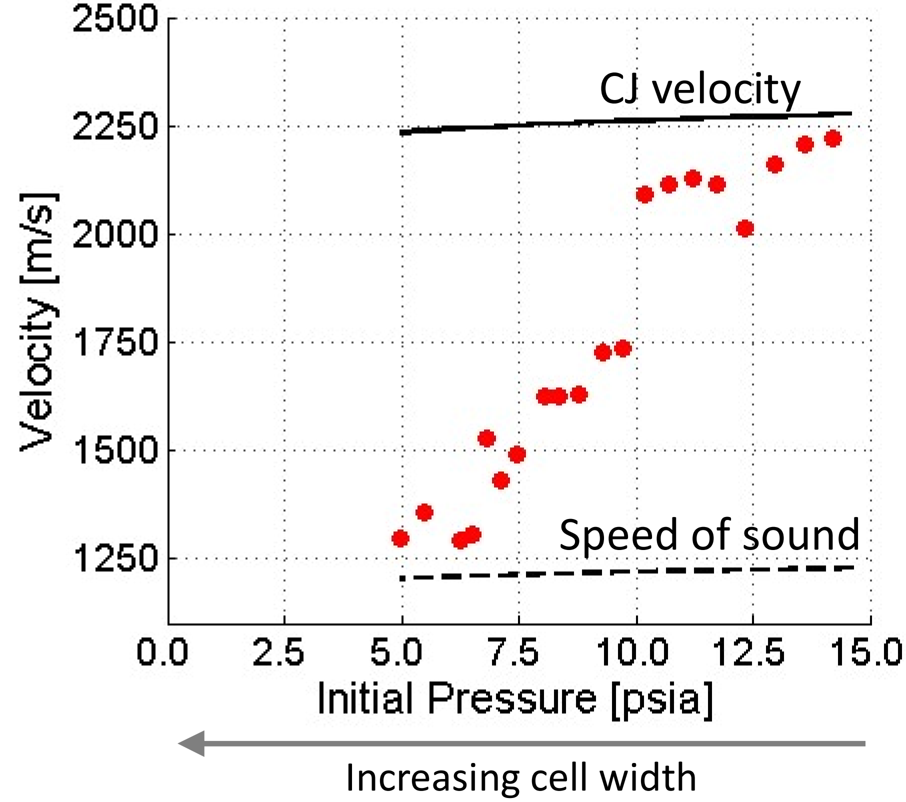
- C_3H_8-O_2 stoichiometric mixture, 13.5 psia initial pressure, 21°C initial temperature
- Time delay calculated using a cross-correlation of the pressure signals
- Detonation velocity calculated from time delay and distance between transducer pairs

Detonation velocity v. initial pressure

$CH_4 + 2O_2$



$CH_4 + 2O_2 + 0.86N_2$

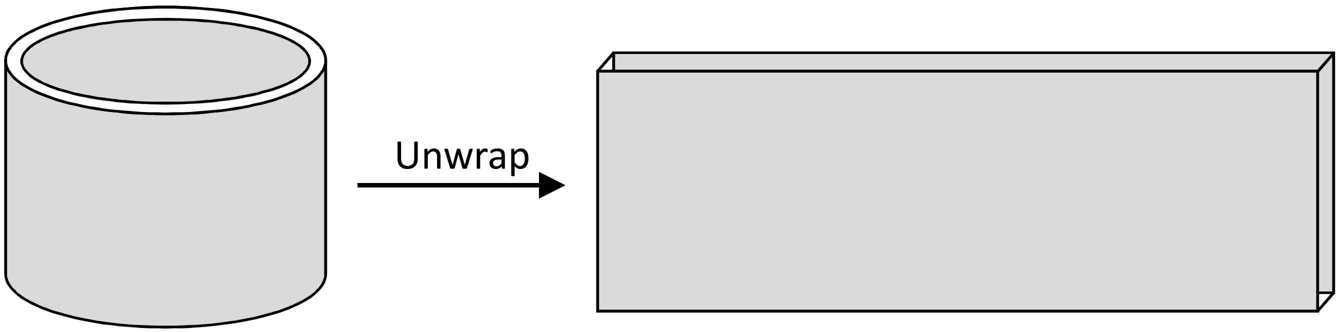


- CH_4–O_2–N_2 mixtures tested with nitrogen concentration between 0% and 30%
- Increasing the nitrogen concentration increased the initial pressure where the measured velocity began to significantly deviate from the predicted velocity

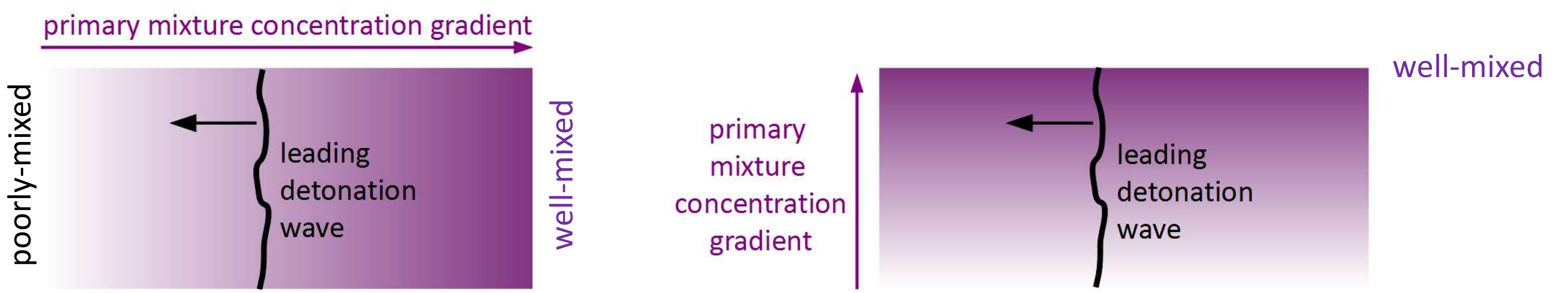
Technical Approach

General technical approach

- In order to increase measurement access, an “unwrapped” RDE will be tested in this study:

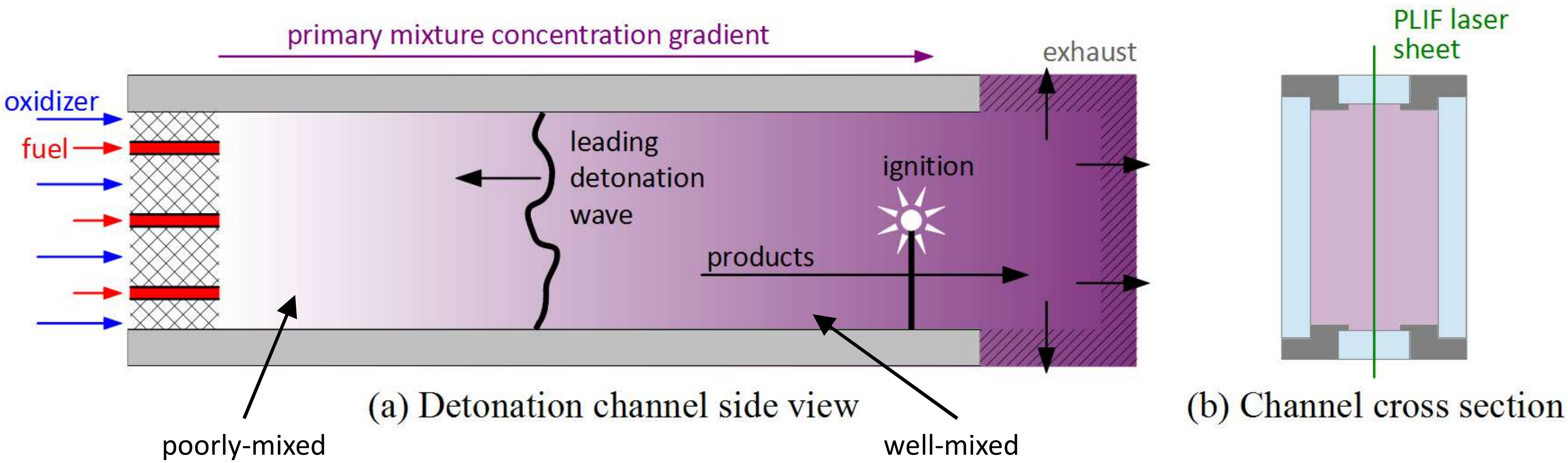


- Two configurations (parallel and perpendicular) will also be tested



(a) Parallel configuration (b) Perpendicular configuration

Parallel configuration illustration

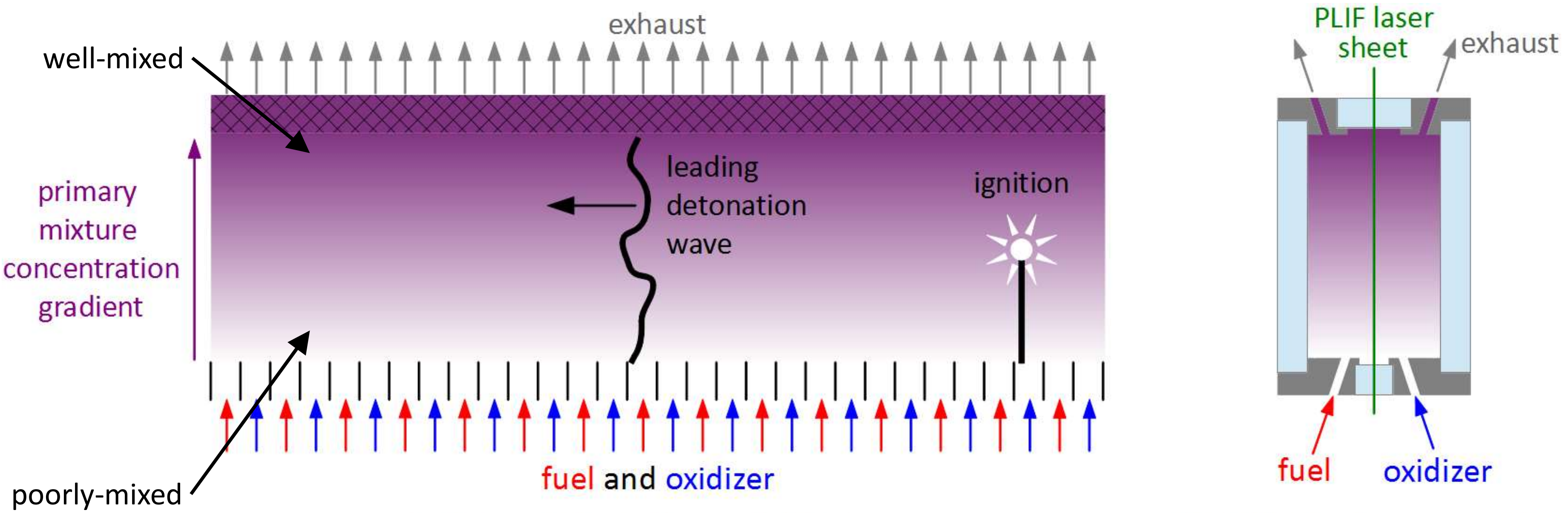


(a) Detonation channel side view

(b) Channel cross section

- Configuration will provide fundamental data on the role of concentration inhomogeneity on detonation propagation
- Spatial variations in fuel concentration measured using acetone-PLIF
- Measurements: pressure fluctuations, chemiluminescence intensity images, smoke foil records, and schlieren images
- The effect of inhomogeneity on detonation pressure, velocity, failure limits, propagation mode (planar or non-planar) will be determined

Perpendicular configuration illustration



(a) Detonation channel side view (b) Channel cross section

- Representative of a rotary detonation engine configuration
- Variable gap widths, combustor lengths, and reactant injection geometries will be tested to better understand the relationship between geometry and detonation propagation
- Same measurements as parallel configuration, plus:
  - concentration inhomogeneity present in a rotary detonation engine
  - leading detonation wave front angle
  - detonation lift-off height above the injector plane

Project Tasks

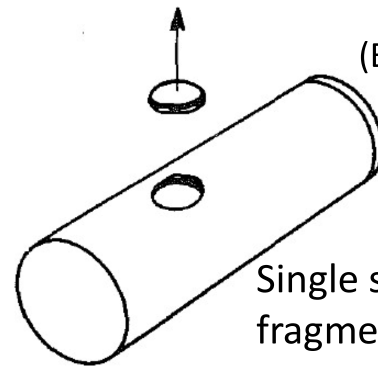
Center for Combustion, Power and Propulsion

Risk management

Several technical risks have been identified:

1. Failure of the detonation channel during testing
   - Due to the unstable nature of the mixtures in this study, pressure piling is possible, leading to equivalent pressures that may cause wall failure
   - Mitigated by previous experience in designing enclosed detonation facilities, porous boundaries/dilution gases in exhaust, high energy "prompt" ignition sources, and protective shield surrounding entire experiment

(Baum, 1988)

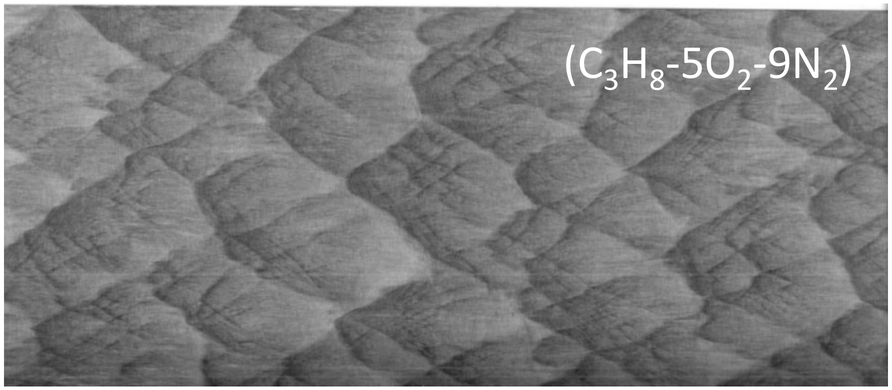


2. Acetone-PLIF measurement of local fuel concentration
   - For H_2-air test mixtures, acetone-PLIF images may not provide an accurate measurement of local fuel concentration due to the difference in diffusive properties between acetone and hydrogen
   - Due to the high injection velocities and turbulence levels typically found in RDEs, mixing may be dominated by turbulence
   - If analysis shows that acetone cannot be used a marker for the local fuel concentration, another appropriate method will be used.

Risk management

3. Smoke-foil records (soot deposited on thin sheet of metal)
   - Used in detonation studies since the 1940s; however, mixture is typically quiescent
   - High velocity flow may remove soot from foil
   - Fixative can be added to soot, or another technique for measuring cell structure will be used (open shutter photography, schileren imaging)

Smoke-foil record example of an unstable mixture (irregular detonation cell structure)



(Austin, 2003)

4. Effects of turbulence on detonation properties
   - To separate out the effects of mixture inhomogeneity and turbulence, additional measurements will be completed with fully premixed, turbulent mixtures
   - Results still relevant since test geometry will match RDE geometry

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Project Milestones

Q3	Design, construction, and assembly of the detonation channel facility
Q4	Local fuel concentration measurements in the parallel test configuration
Q4	Initial detonation property measurements in the parallel test configuration
Q6	Local fuel concentration measurements in the perpendicular test configuration
Q7	Initial detonation property measurements in the perpendicular test configuration
Q9	Successful operation of the test facility at elevated initial pressure and temperature
Q12	Detonation structure characterization for property normalization across all conditions

- Seven milestones were chosen for the three year project. These milestones are all necessary to achieve the goals of the project and completion of these milestones will indicate progress towards the overall project goals and objectives.

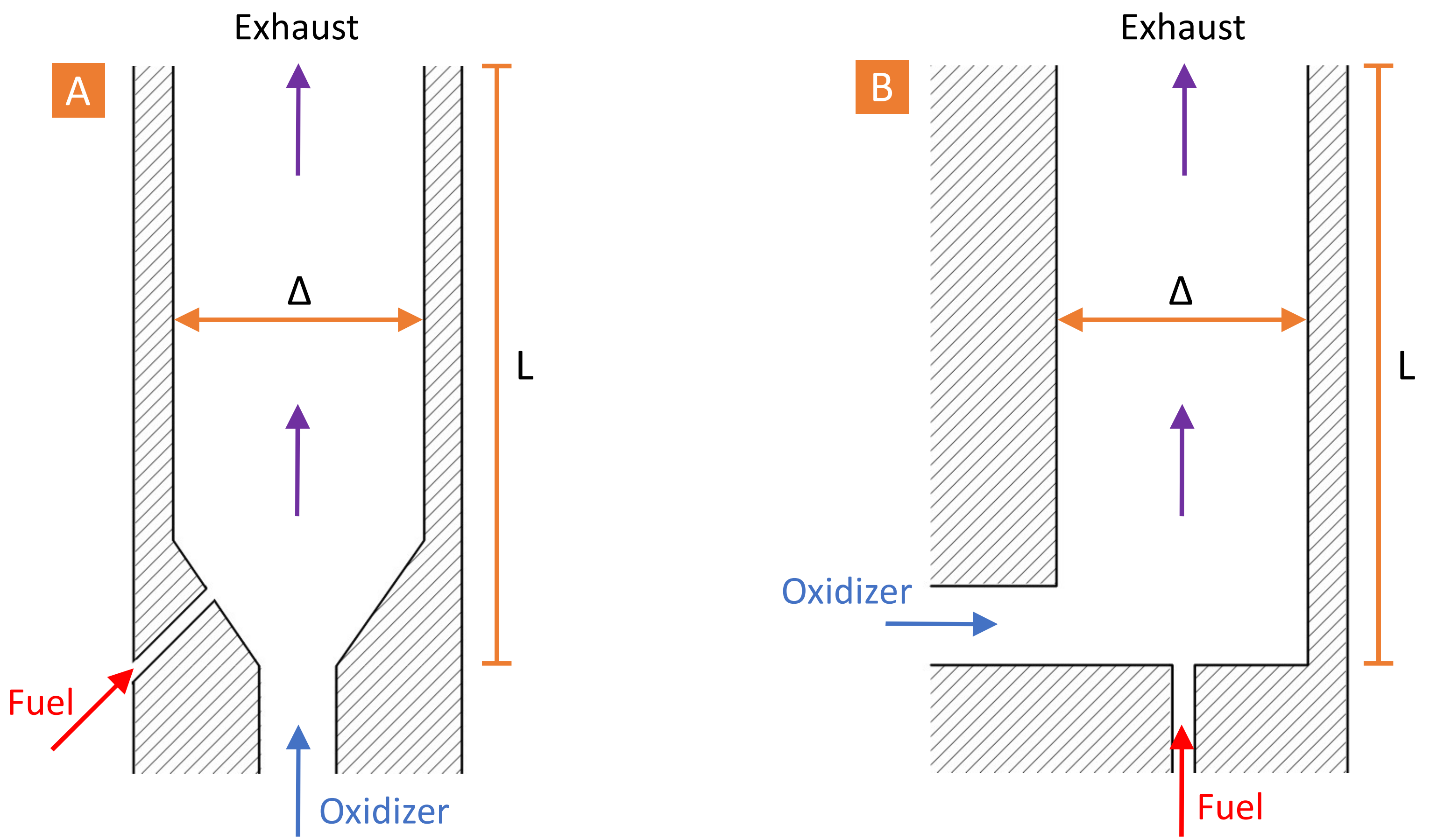
Summary of RDE operating characteristics and dimensions

Author	Location	Year	Mixture	Frequency [kHz]	Length (L) [mm]	Gap Width (Δ) [mm]	Cell Width* [mm]
Liu	Hunan, China	2012	H_2 – air	~5.5	75	5	6 – 10
Thomas	Wright-Patt	2011	C_2H_4 – O_2	~8	153	2, 6, 10	2 – 3
Shank	Wright-Patt	2012	H_2 – air	2.9 – 3.3	140	7.6	6 – 10
Braun	UT Arlington	2010	H_2 – O_2 C_3H_8 – O_2	15.6 13.7	127	12.7	1 – 2 0.5 – 1
Kindracki	Warsaw University of Technology	2011	CH_4 – O_2 C_2H_6 – O_2 C_3H_8 – O_2	13 – 14	30 mm + conic section	4	2 – 4 1 – 2 0.5 – 1
Bykovskii	Lavrent'ev Institute (Novosibirsk)	1980 1980 2008 2011	CH_4 – O_2 C_2H_2 – O_2 H_2 – O_2 H_2 – air	13 – 14 13 – 17 ~40 1.4	40 – 85 20 – 85 100 395 or 510	5 1.25 – 5 5 23	2 – 4 0.1 – 0.2 1 – 2 6 – 10

*Unconfined, stoichiometric mixture, atmospheric pressure

- Wide variety of mixtures and geometries have been tested
  - H_2 + Air or O_2 + hydrocarbon, due to narrow gap widths typical of RDEs
  - Combustor lengths (L) typically greater than 10× gap widths (Δ) – high aspect ratios
- Frequency of wave propagation determines reactant refill time

RDE configuration illustrations (cross sections through combustor)



- Two typical RDE configurations are shown above
  - Fuel is typically injected through holes
  - Oxidizer is injected through either a slot or holes

Δ: 2 – 23 mm

L: 20 – 510 mm