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# The Development of a Pre-Chamber Combustion System for Lean Combustion of Liquid and Gaseous Fuels


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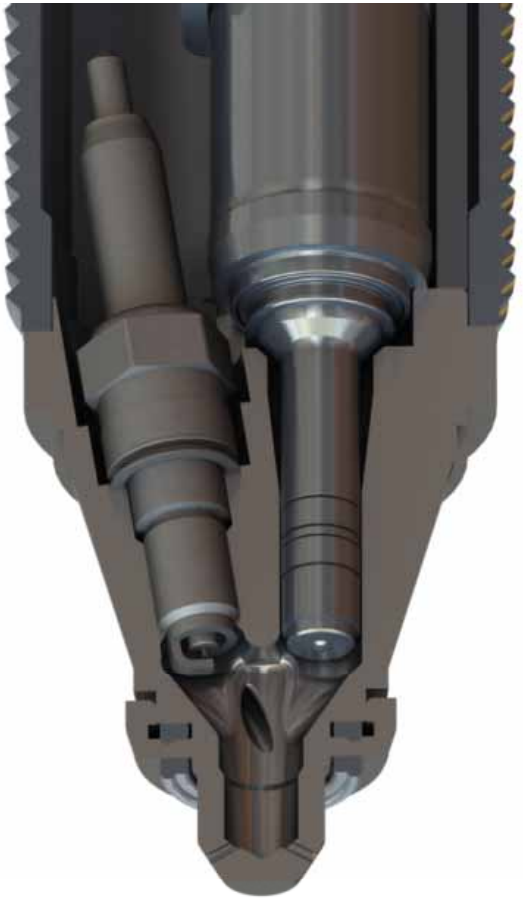

# Lean Combustion Approaches

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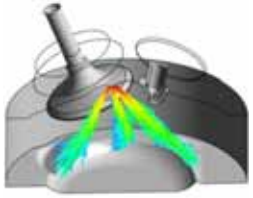
Lean Combustion



- Homogenous Spark Ignition
  - Comb. stability limited to ≈ λ= 1.8
  - Ignition energy limited
  - Lean $NO_x$ trap required
- Stratified Spark Ignition
  - Close spaced injector & plug
  - Lean $NO_x$ trap required
  - Multi spark needed for full potential
- Homogenous Turbulent Jet Ignition
  - High energy ignition from a pre-chamber turbulent igniter
  - Enables λ> 2.5 hence low $NO_x$
  - Multiple ignition points in main chamber

# Natural Gas Application Approaches

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- Spark Ignition CNG or LNG
  - Typically run stoich
  - 3-way catalyst required
  - Oil formulation is critical
- Bi-Fuel CNG/gasoline
  - 2 separate fueling systems
- High Pressure Direct Injection (HPDI) LNG w/ Diesel Pilot
  - High efficiency
  - DPF and SCR required
- Dual Fuel CNG/diesel
  - Can substitute up to ~70% CNG
- TJI CNG pre-chamber or CNG single fuel
  - CNG used for pre-chamber only or as single fuel
  - Enhanced pre-chamber mixing enables further lean limit extension

*Acknowledgement: Anthony Greszler – Volvo Trucks*

# MAHLE Powertrain Turbulent Jet Ignition System

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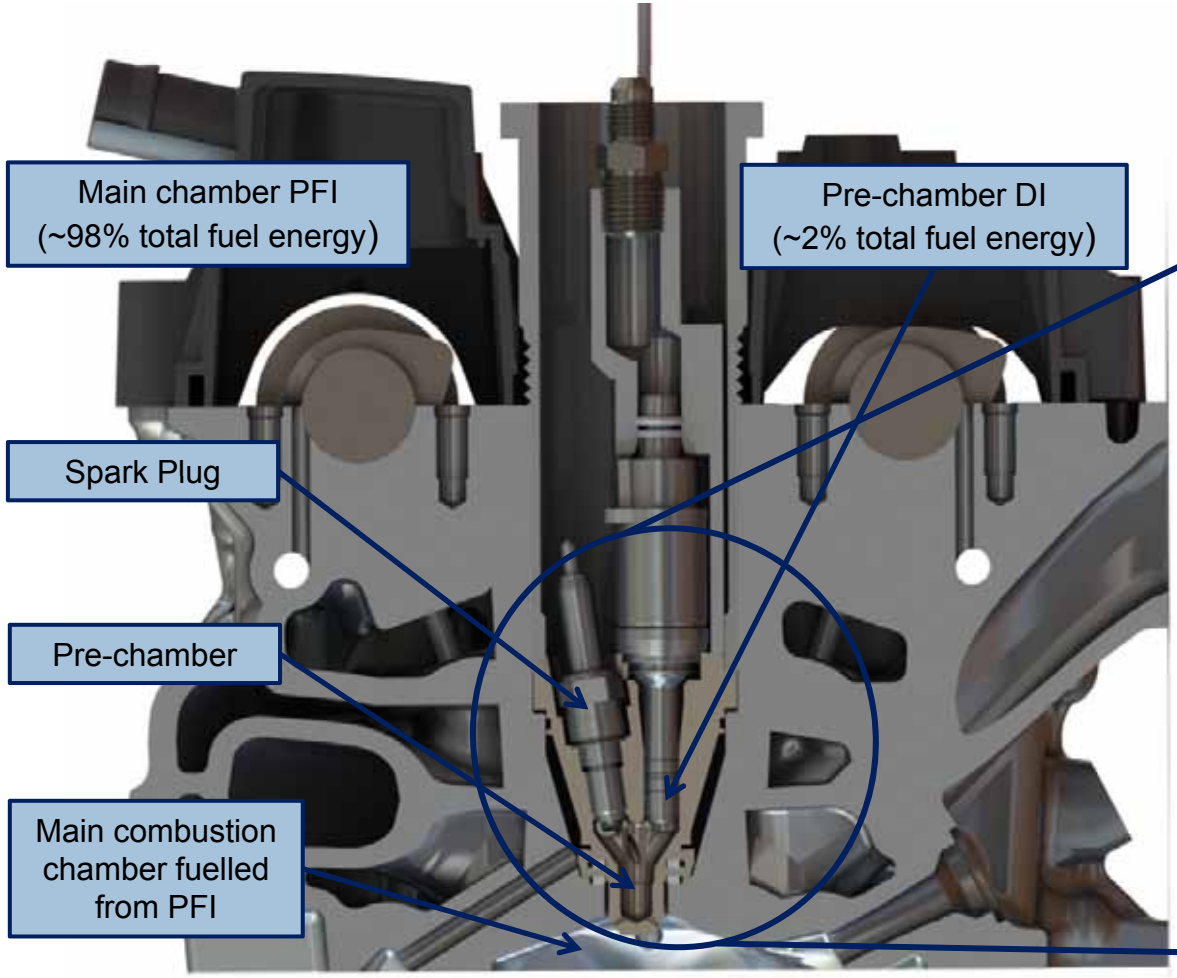
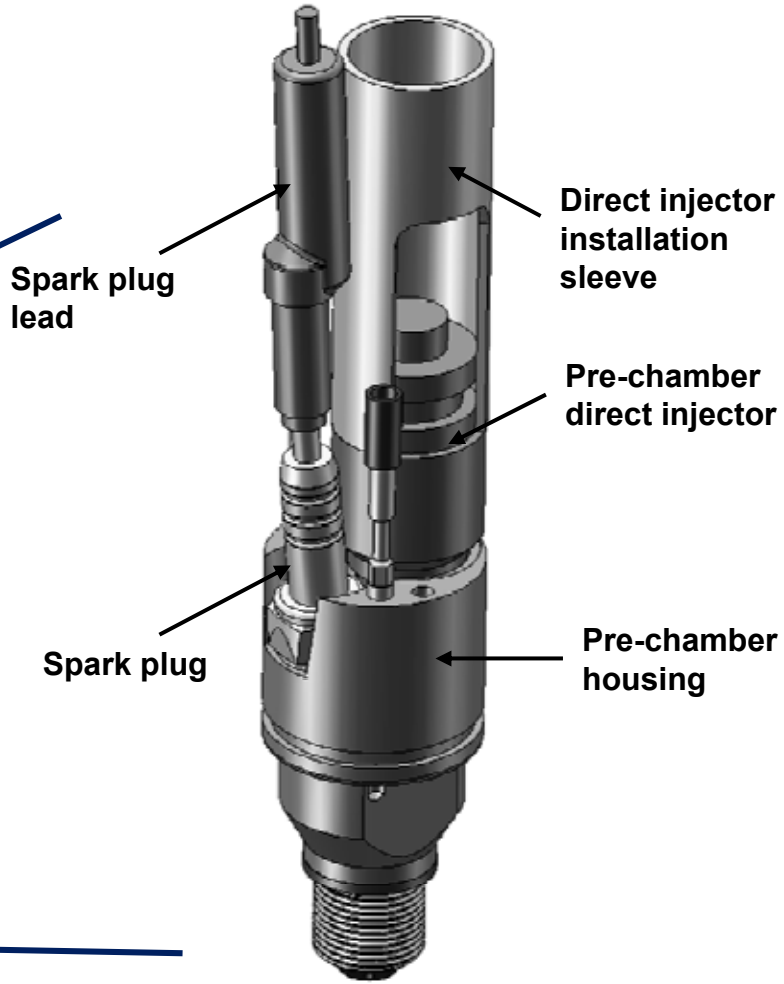
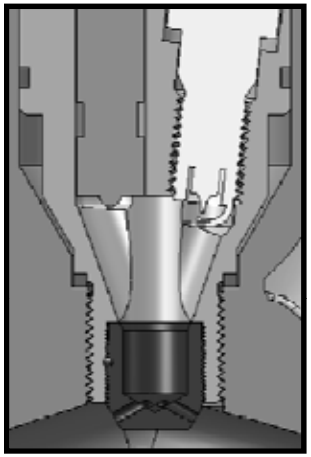
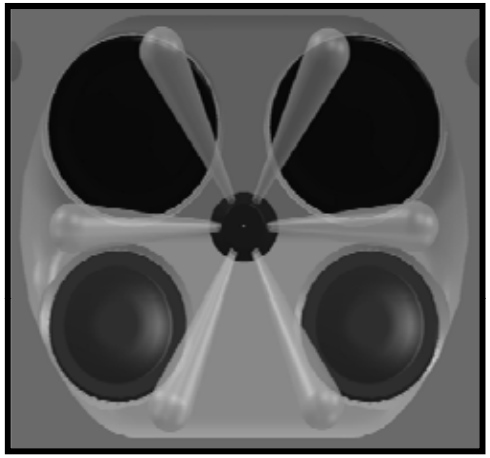
- Turbulent Jet Ignition (TJI) assembly simply replaces the spark plug in a modern engine design



# MAHLE Powertrain Turbulent Jet Ignition System





- Pre-chamber assembly has minimal volume and is fuelled to $\lambda \approx 1$ by DI injector
- Pre-chamber fuelling is up to 4% of total fuel flow
- Pre-chamber mixture is ignited by conventional spark plug
- Partially burned combustion gases forced through 6 nozzle orifices into the main chamber
- Nozzle orifices targeted to direct jets throughout main chamber
- Main chamber combustion proceeds from ignition sites initiated by partially burned contents of these jets

# DOE Project Objectives

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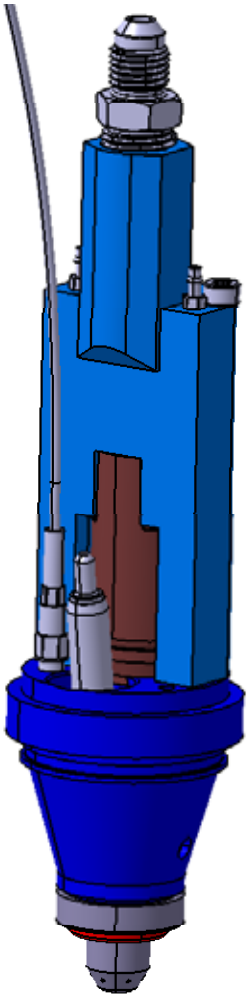
- **US Dept. of Energy project**: optimize pre-chamber geometry and hardware in order to achieve:
  - 45% Thermal Efficiency
  - 30% predicted drive cycle fuel economy improvement
  - Cost effectiveness with minor modification to engine hardware
  - Demonstrate potential to meet US EPA emissions
- Enabling Technology: TJI + boosting
- Phase 1 focus
  - Optical and thermo engine testing focus on combustion sensitivity to TJI hardware variations
  - CFD focus on mixing/scavenging



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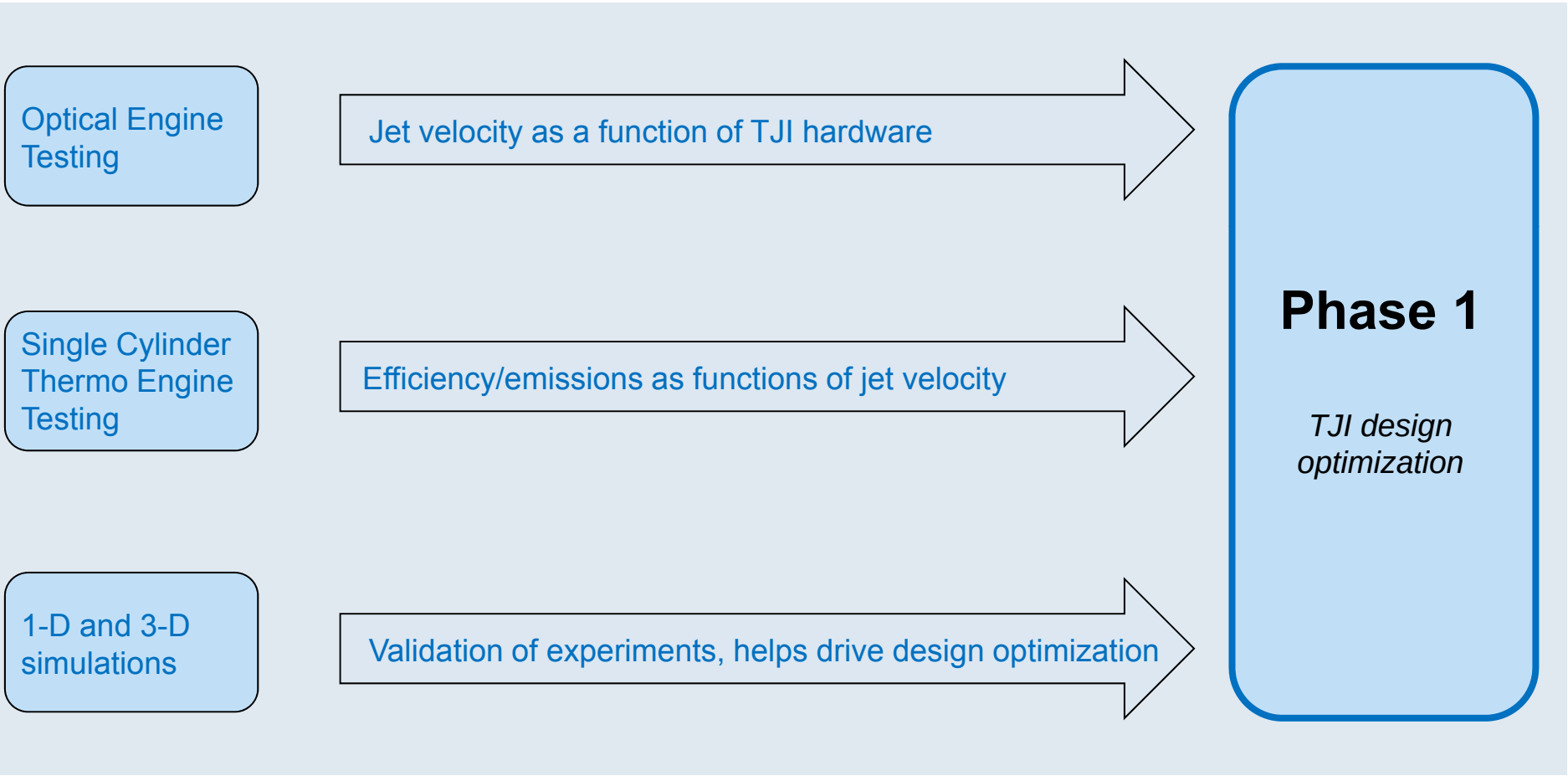
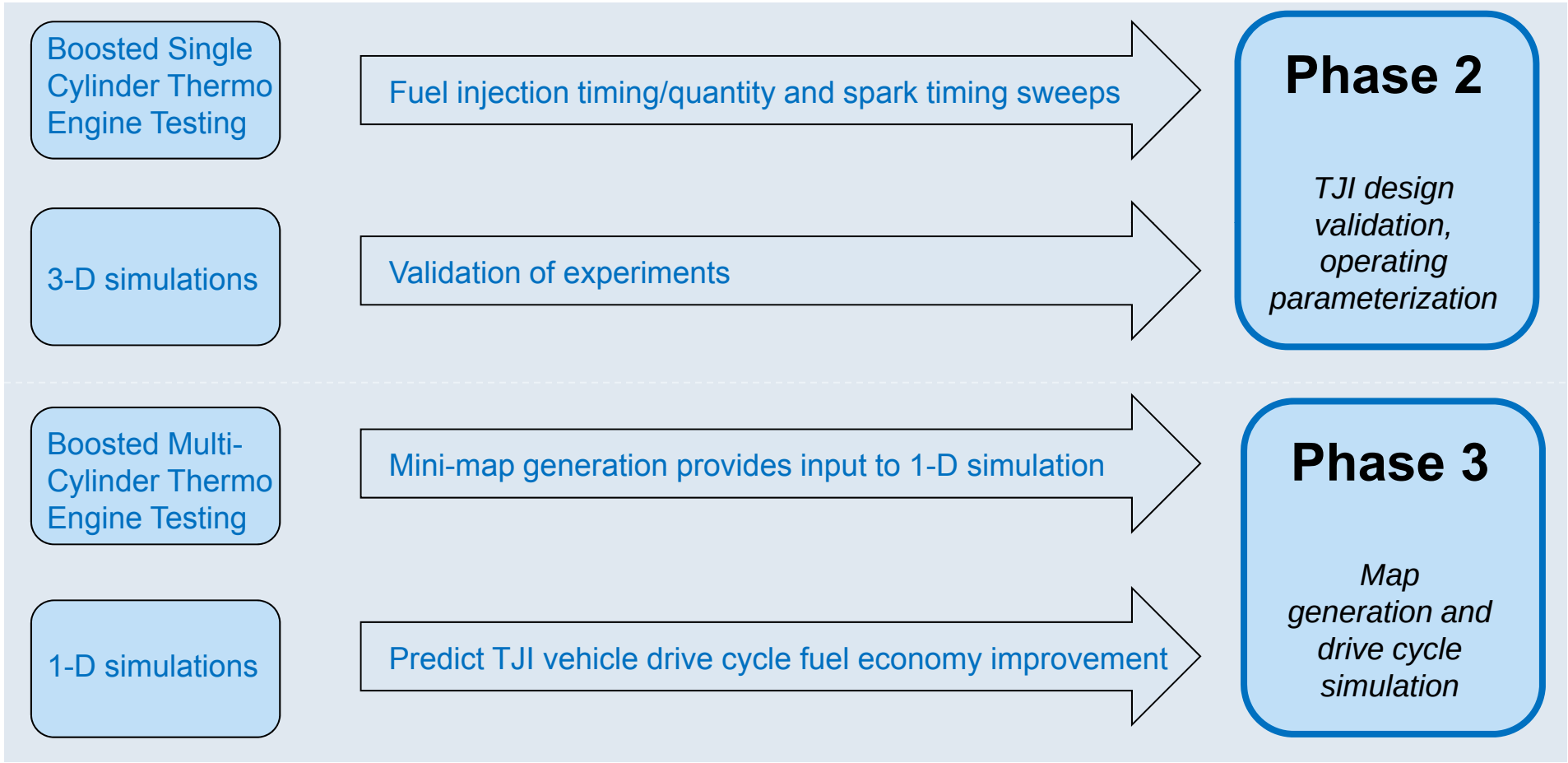
# Phase 1 Approach



# Phases 2 and 3 Approaches



# Testing: TJI Variations

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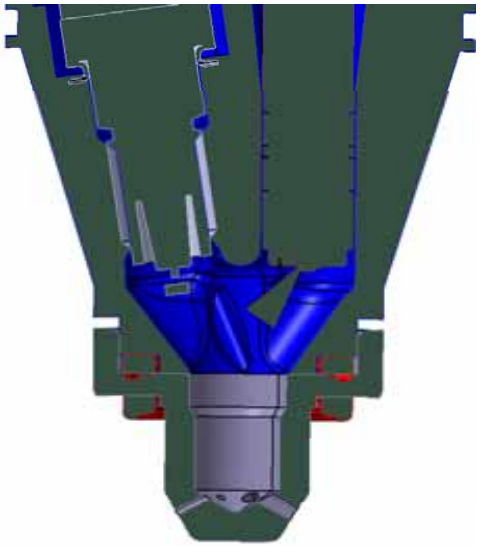
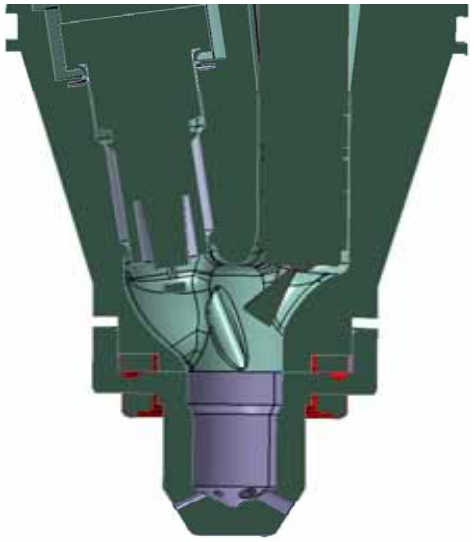
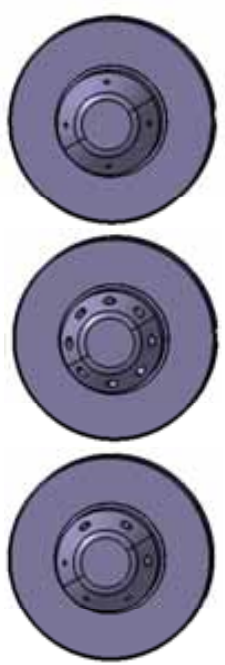
- Phase 1 optical and thermo engine testing focus on pre-chamber mixing and combustion as a result of TJI design variations
  - 2 distinct TJI geometry variations
  - 11 distinct nozzle variations







# Optical Engine Testing

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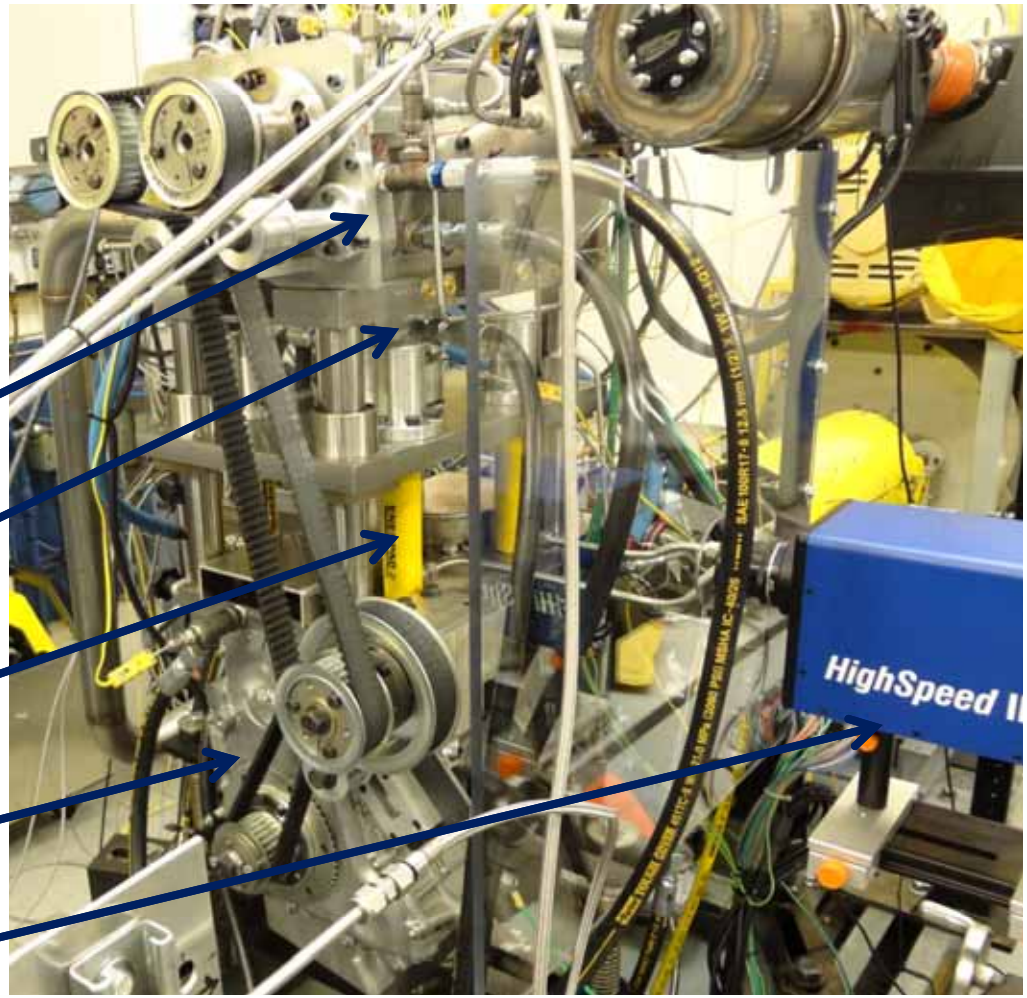
- Optical engine successfully designed and assembled in-house

- Purpose: determine TJI design effects on jet characteristics



# Optical Engine Results

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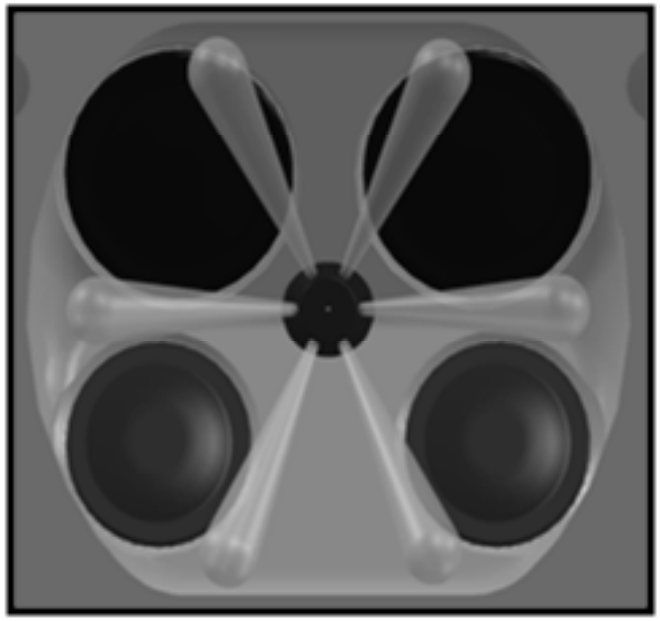
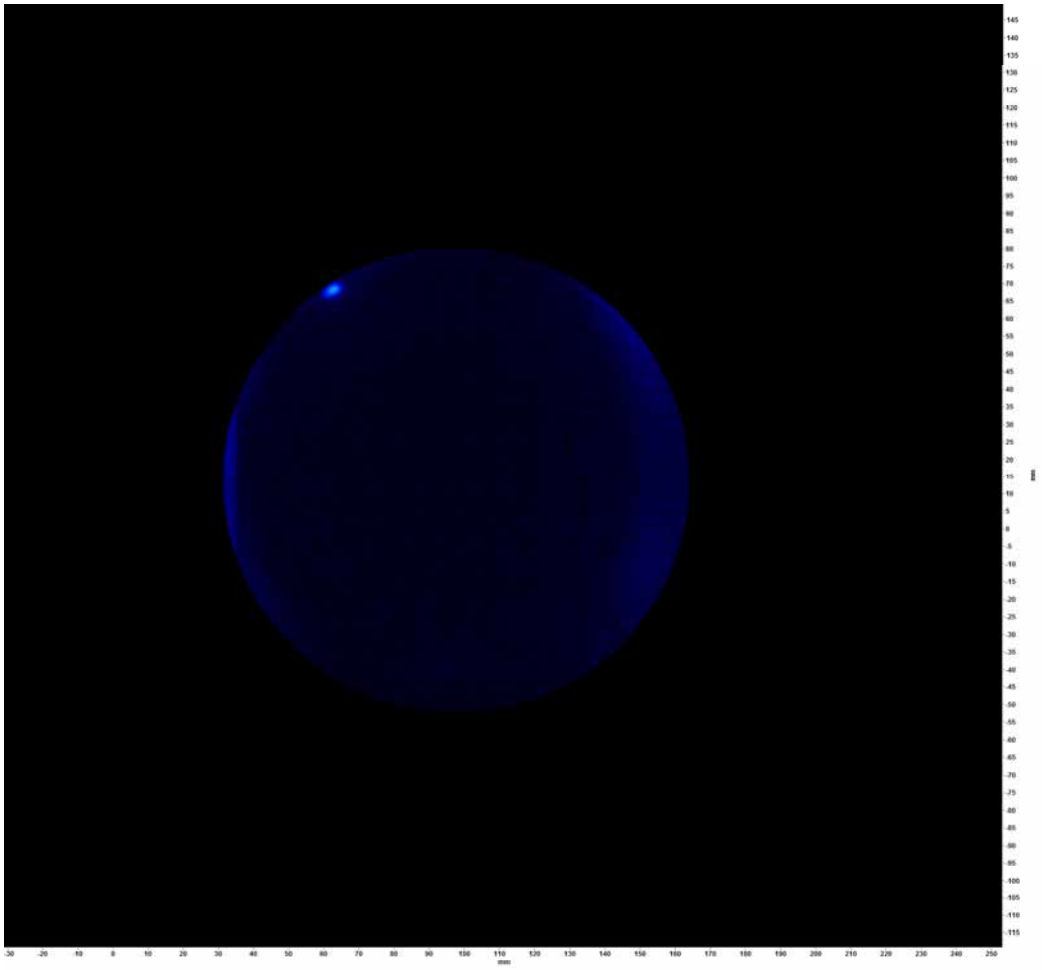
- Base TJI hardware w/ fueled pre-chamber
- Operating conditions
  - 1500 rpm, 3.5 bar IMEPg, λ = 1.1
- Color contours show light intensity and represent cylinder temperature





# Optical Engine Results

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- Data analyzed in terms of jet velocity/penetration/variability and main chamber ignition site count and distribution through the use of correlation tables

- Findings:
  - Jet penetration prior to ignition strongly correlated to jet velocity
  - Low jet velocity → low degree of penetration → longer combustion duration
  - High jet velocity → high max penetration → fewer ignition sites due to wall quenching

- **Conclusion:** Necessary to target jet velocity in order to maximize ignition site distribution while preventing jets from traveling to walls and quenching

- Next step: identify the relationship between jet characteristics and engine performance parameters ⟶ Synthesize optical engine data with metal engine data

# Single Thermodynamic Engine Overview

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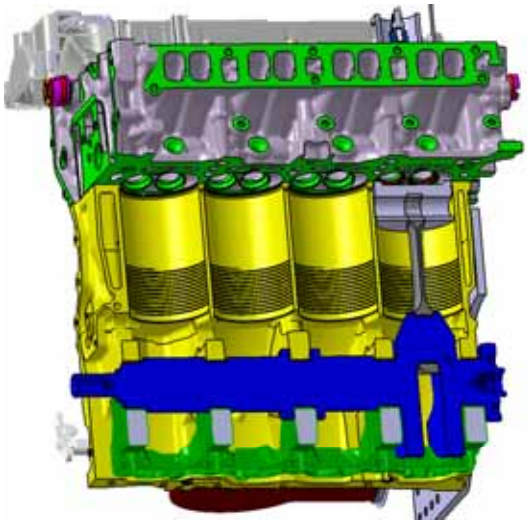
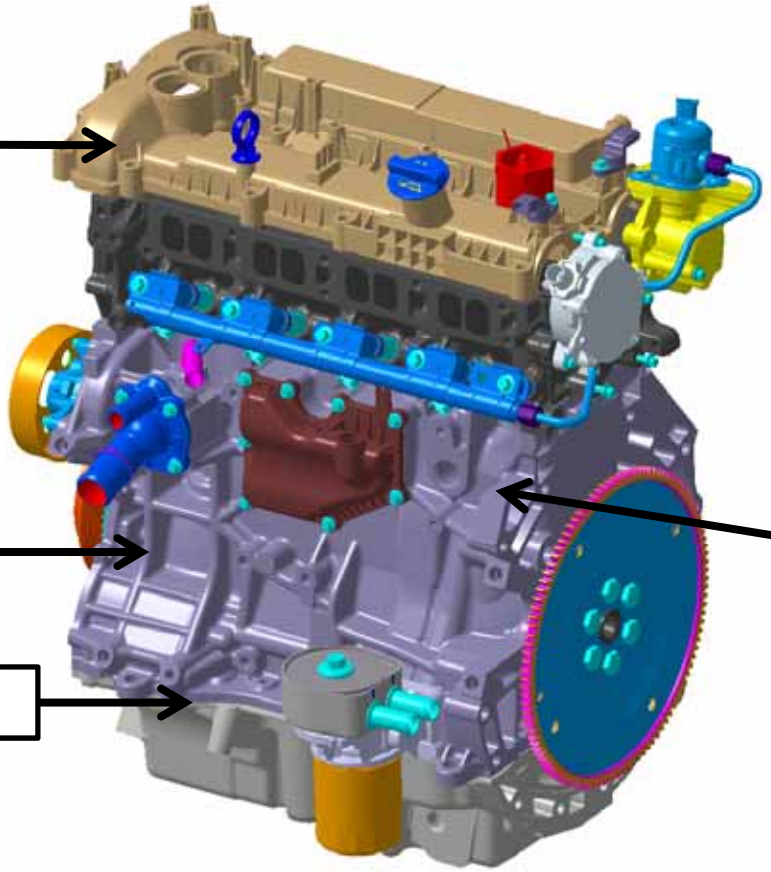
- Single cylinder thermodynamic engine designed and assembled in-house
- Metal engine counterpart to optical engine



Prototype Ford 2.3L Cylinder Head

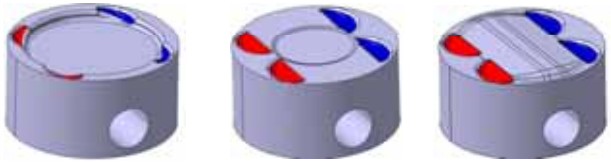
Custom Crankshaft



Production Ford 2.0L Block

Custom Connecting Rod And Piston

10:1 12:1 14:1



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# Thermodynamic Single Cylinder Testing

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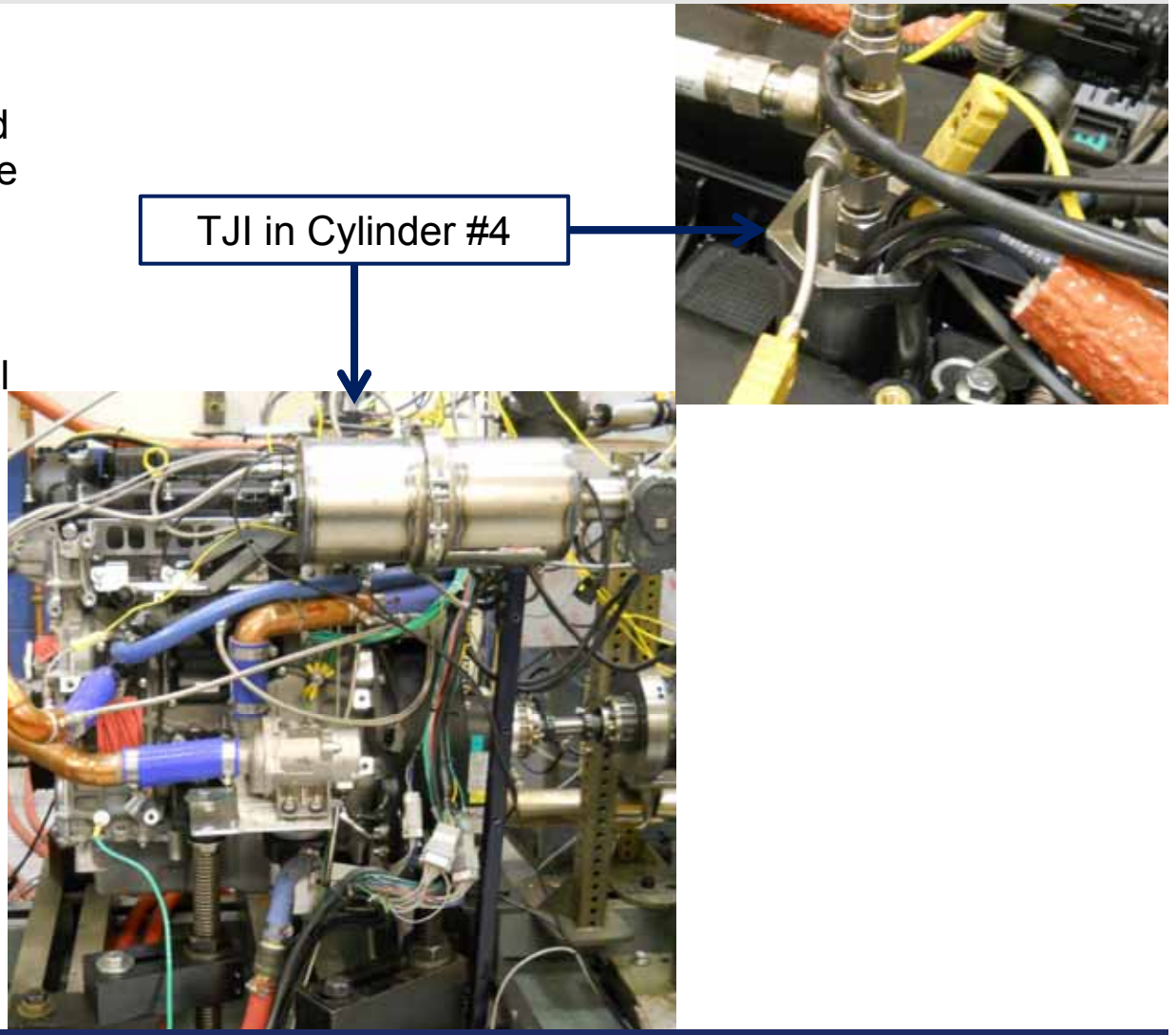
- Purpose:
  - Test multiple pre-chamber and nozzle geometries and analyze performance variations
  - Synthesize combustion performance with jet characteristic data from optical engine
  - Provide correlation data for CFD analysis
- Data processed and synthesized with optical data



# Thermo Engine Results

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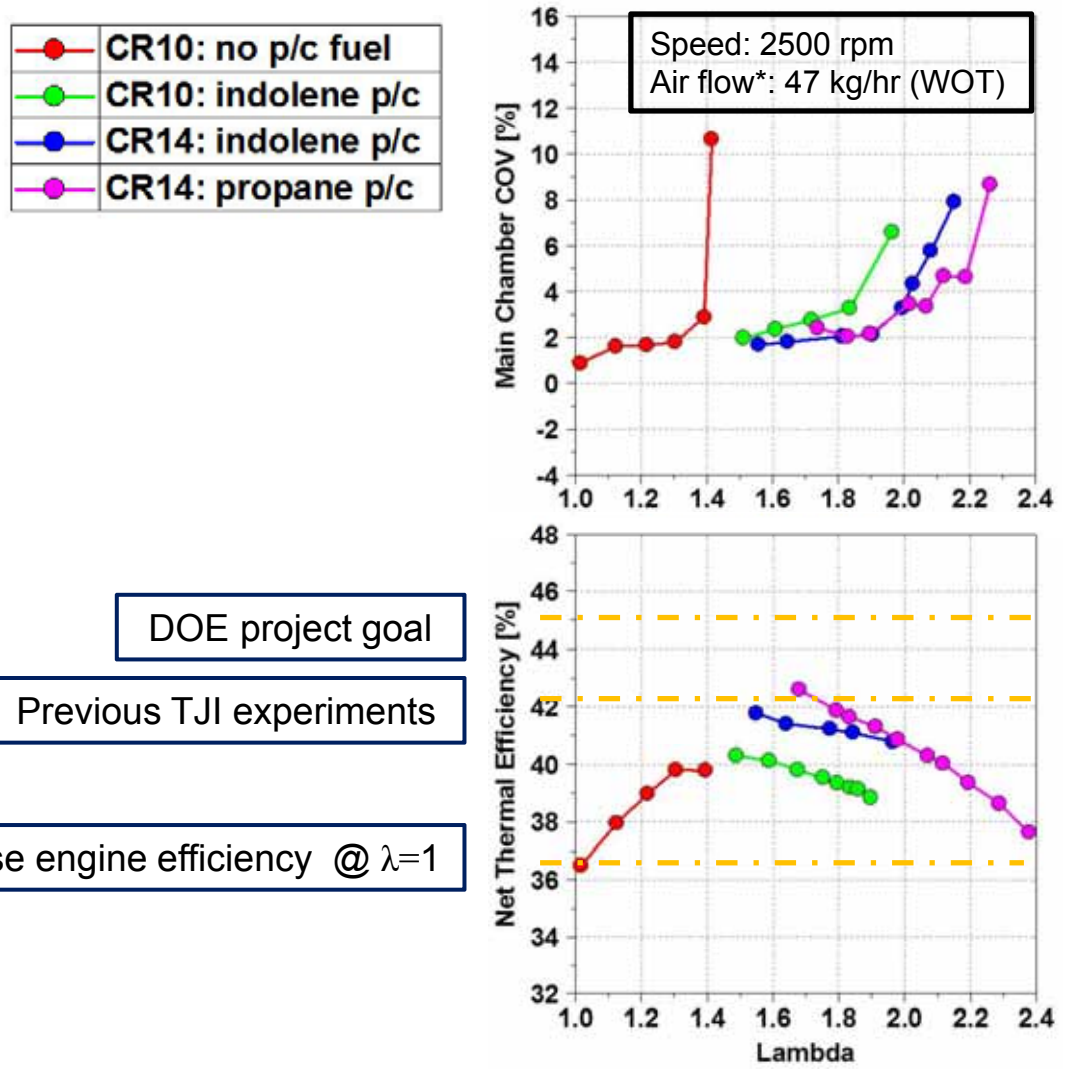
- TJI effectively extends the lean limit of a standard SI engine by maintaining stable combustion
  - Enables ultra-lean (λ>2) operation
- Results demonstrate:
  - Significant thermal efficiency gain over base engine
  - Results comparable to previous TJI experiments
  - Propane-fueled p/c demonstrates superior thermal efficiency
- Further analysis ongoing




*Note: 47 kg/hr = 8.7 bar IMEPg @ stoich*

# Liquid Fueled Pre-Chamber Case – CO2 Fraction

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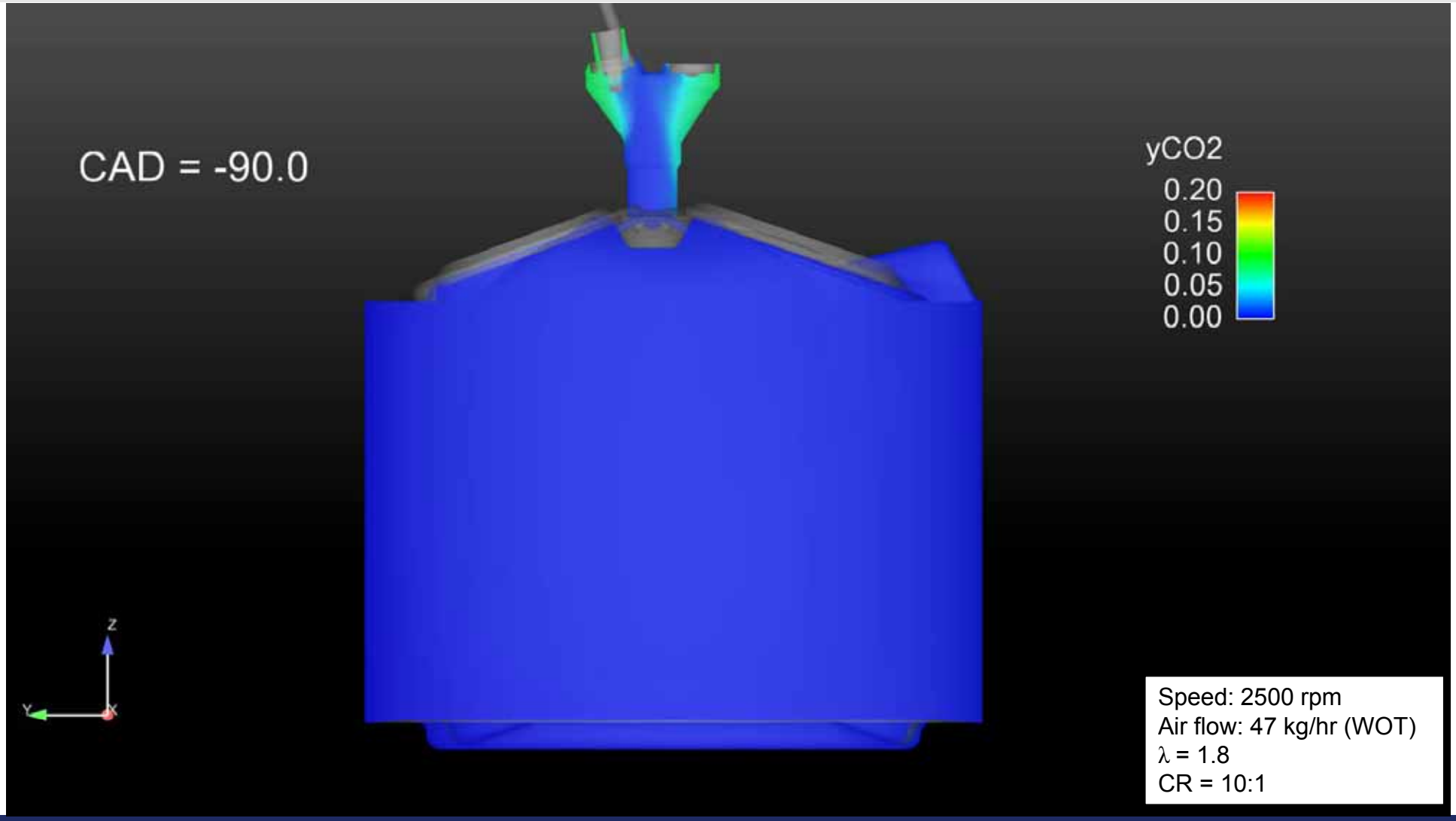

# Single Cylinder Test Engine

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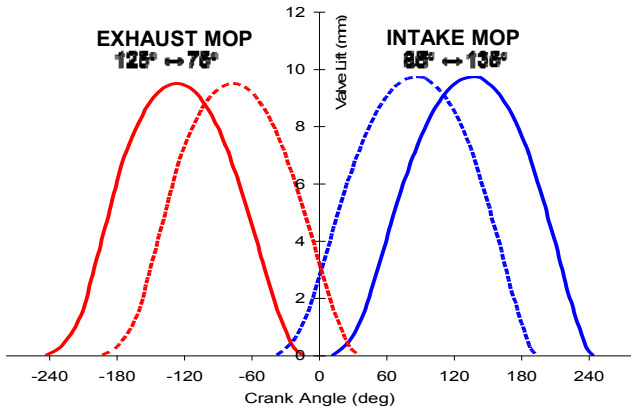
| Engine Basis | GM Ecotec LE5 |
|---|---|
| Engine Type | Single Cylinder Naturally aspirated |
| Main Chamber Fuelling | Port fuel injection |
| Displacement | 0.6 liter |
| Bore x Stroke | 88 x 98 mm |
| Compression ratio | 10.4 |
| Octane number | 91 |

**TJI single cylinder**

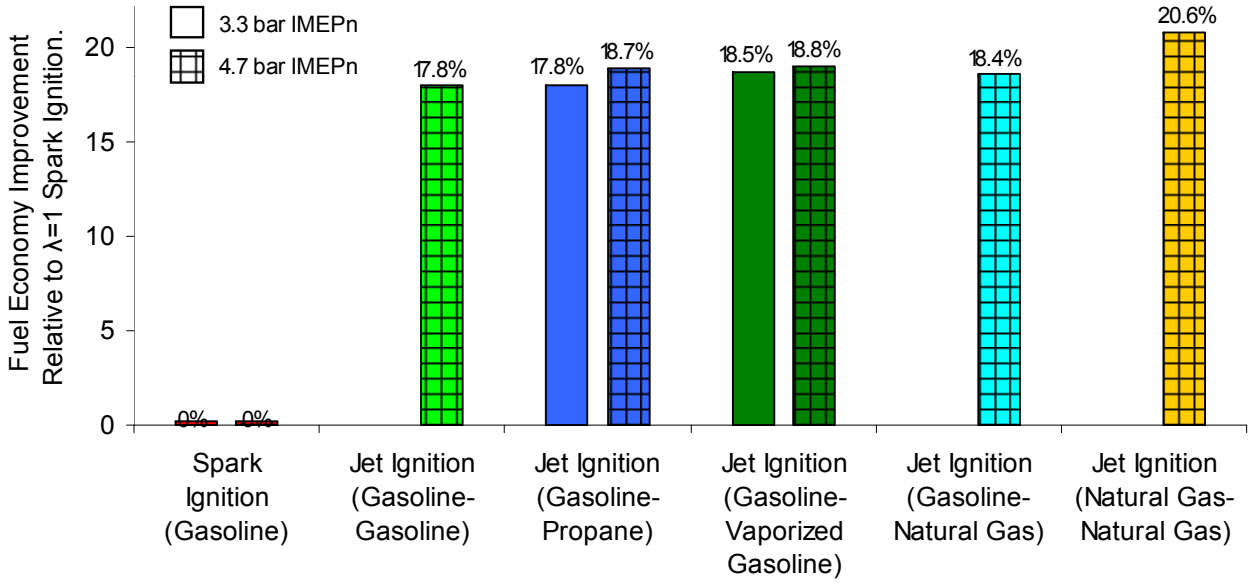



**Dual VVT – Cam Phasers**

MOP= Maximum Opening Point

# TJI Results: Various Fuels

- Split fuel (gaseous pre-chamber) approach offers some efficiency benefits vs. single liquid fuel
  - Higher degree of homogeneity in pre-chamber
  - No wall impingement
- Highest efficiency gain with single gaseous fuel



Summary

# TJI: Lean Combustion of Liquid and Gaseous Fuels

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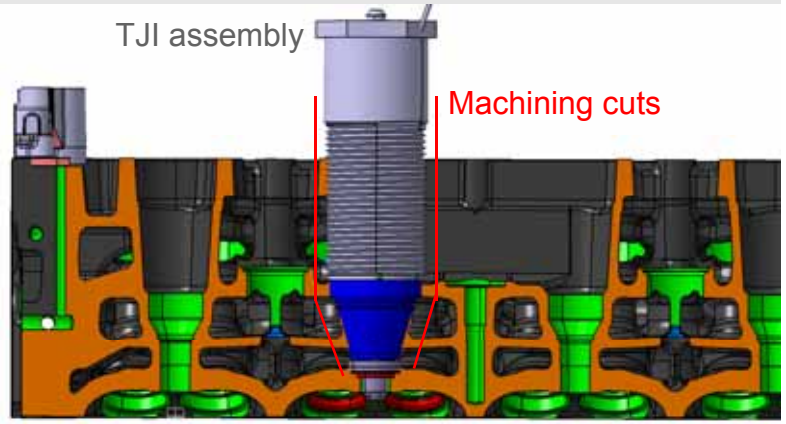
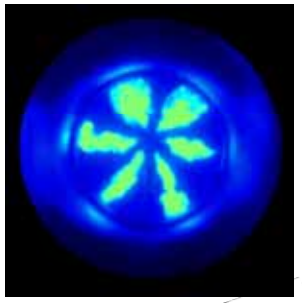
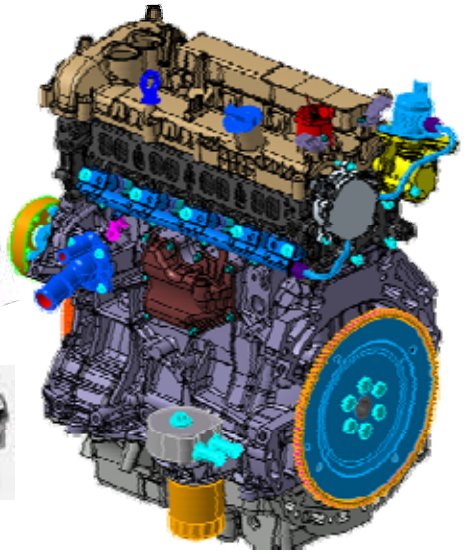
- TJI is an effective enabling technology for ultra lean combustion
  - High thermal efficiency
  - Low NOx
- MPT researching fundamental characteristics of TJI
  - Optical and thermodynamic single cylinder engines
  - CFD investigation of mixing/scavenging
- Synthesized data will describe correlation among TJI design variations, jet characteristics, and performance
  - SAE Technical Paper 2014-01-1195
- TJI provides excellent platform for dual fuel (liquid/gaseous) and single gaseous fuel applications





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## Thank you


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# Back Up Slides

# Optical Engine Testing

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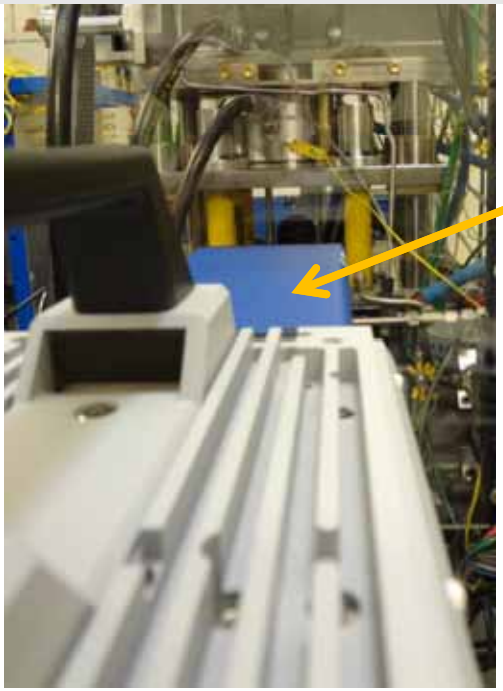
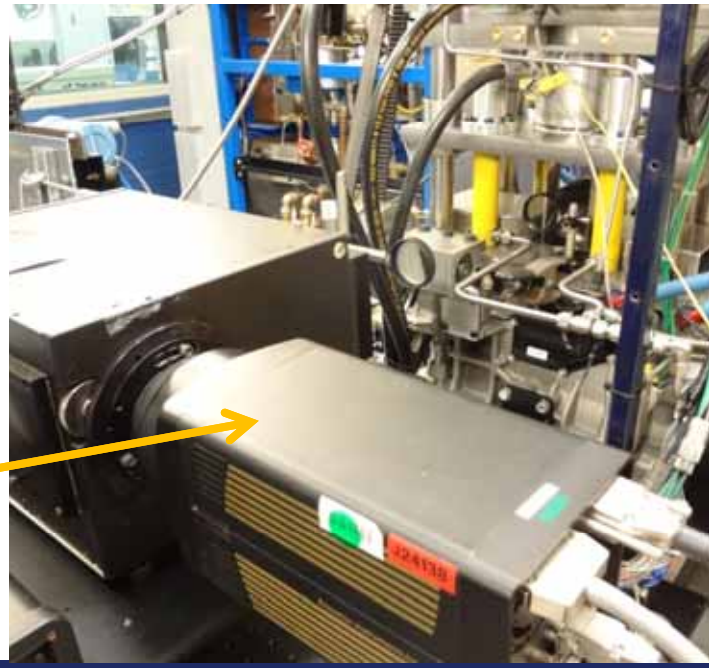
- Design proved to robust, test procedure proved to be effective
- Test Setup
  - High-speed camera acquired chemiluminescent images at 10kHz (~1 frame per CAD @ test speed)
  - High-speed spectrometer acquired spectra (primarily OH, CH)
- Spectral Energies LLC supplied high-speed camera and spectrometer setup and assisted with test setup



High-speed camera



High-speed spectrometer

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# Optical Engine Results

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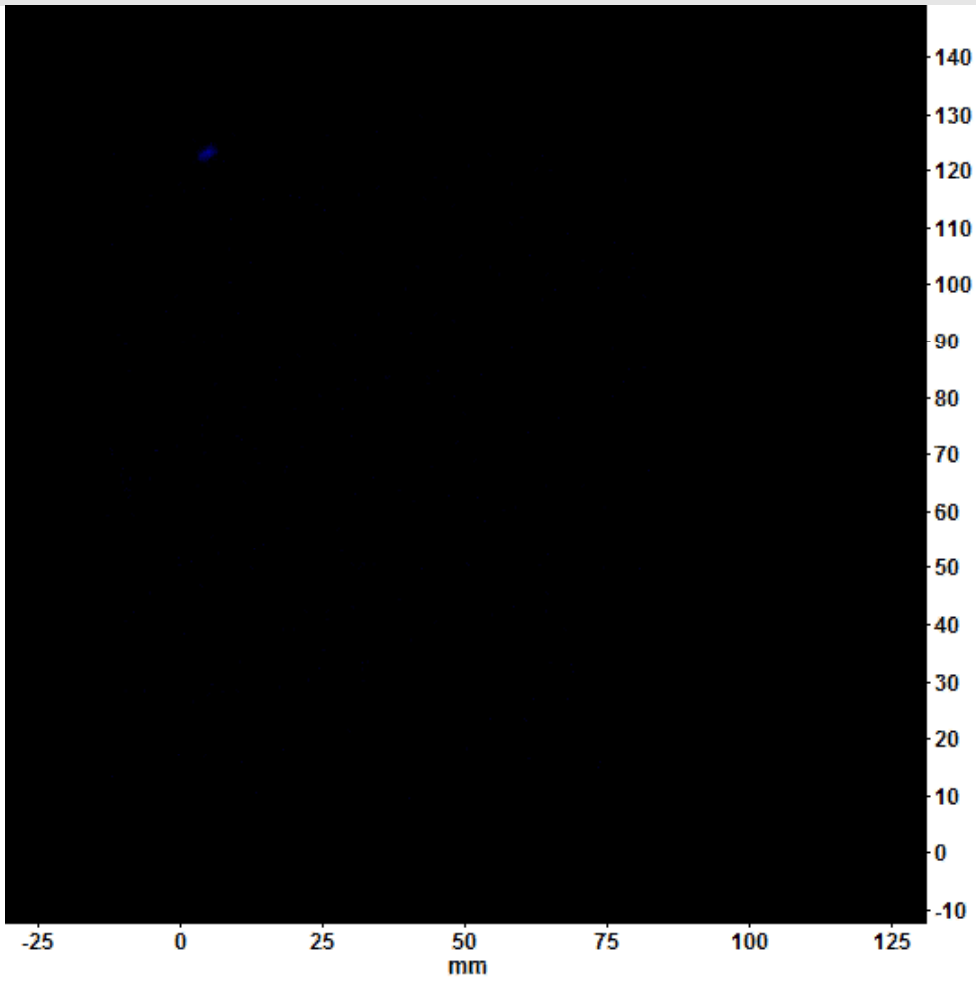
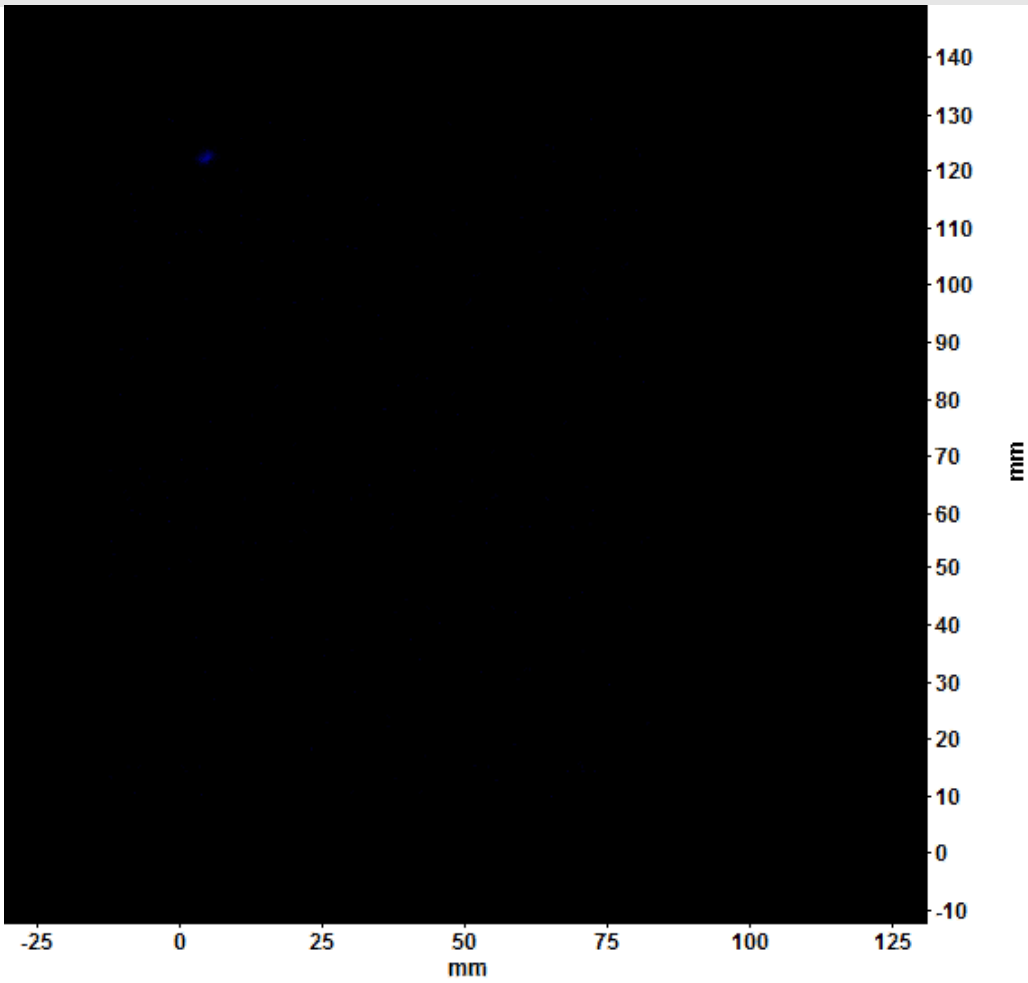



Small nozzle hole diameter




Large nozzle hole diameter