Next-Generation Ultra Lean Burn Powertrain
DE-EE0005656

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MAHLE Powertrain, LLC

6/12/2015

Project ID: ACE087

Project Outline

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Timeline

Start Date: February 1, 2012

End Date: June 30, 2015

Percent Complete: 85%

Project Goals/ACE Barriers Addressed

- 45% thermal efficiency on a light duty SI engine with emissions comparable to or below existing SI engines *(A, B, C, D, F)*
- 30% predicted drive cycle fuel economy improvement over comparable gasoline engine vehicle *(A, C, H)*
- Cost effective system requiring minimal modification to existing hardware *(G)*

Budget

Contract Value (80/20): $ 3,172,779

Gov't Share:	$	2,499,993
MPT Share:	$	672,796

Funding received in FY2014: $ 940,450

Funding for FY2015: $ 124,203

Partners & Subcontractors

Ford

Test engine platform

DELPHI

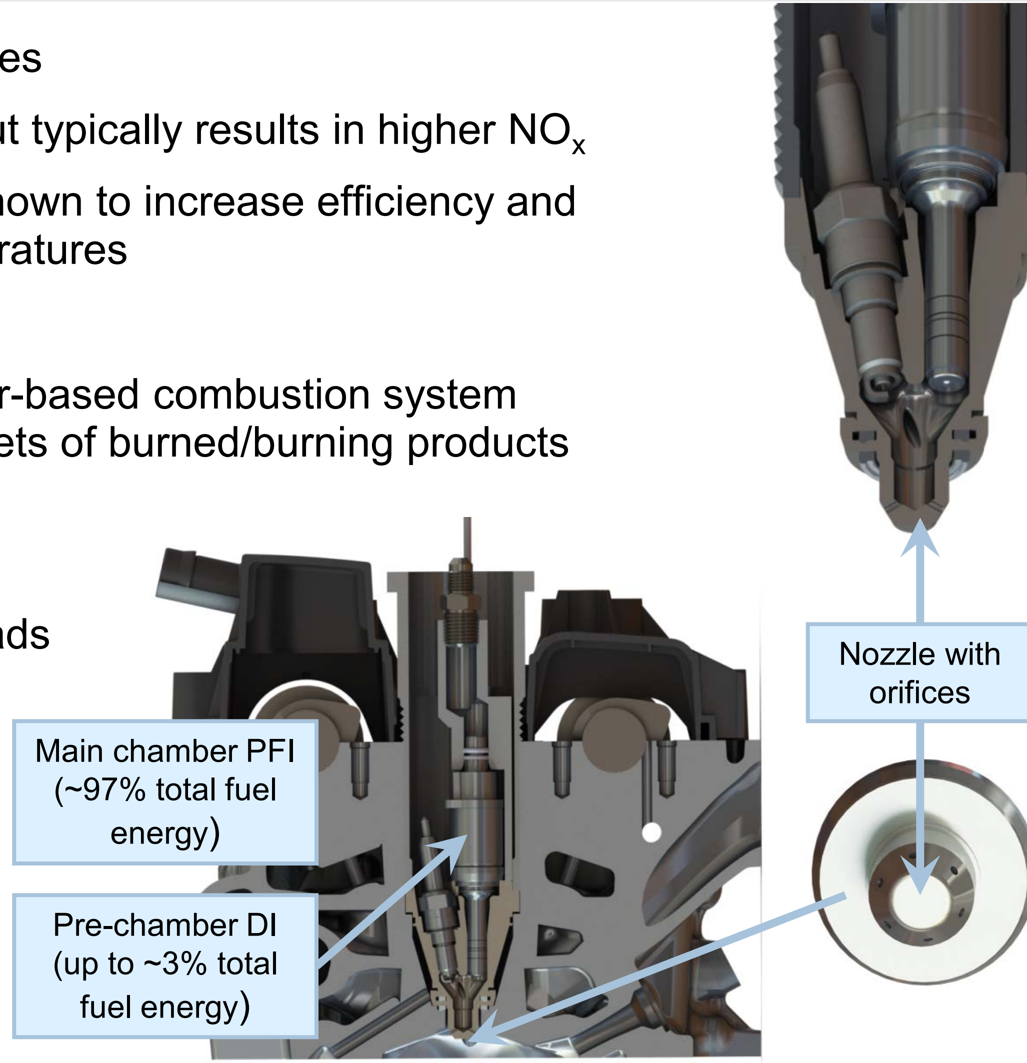
Custom injector design and development

Background

- Demand for highly efficient and clean engines
  - Lean operation increases efficiency but typically results in higher NO_x
  - Ultra lean operation (λ>2) has been shown to increase efficiency and reduce NO_x due to low cylinder temperatures

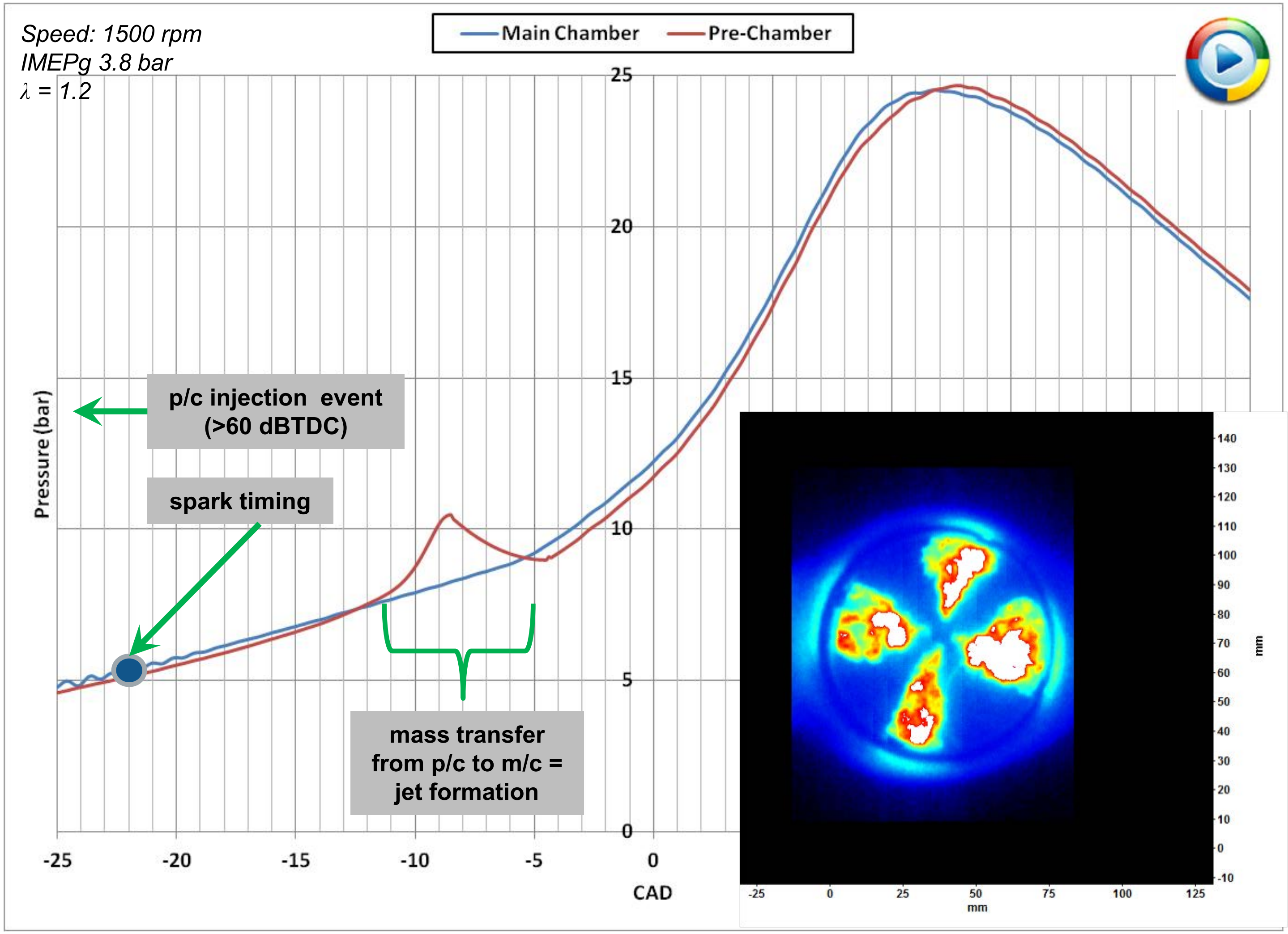
- Turbulent Jet Ignition (TJI) is a pre-chamber-based combustion system offers distributed ignition from fast moving jets of burned/burning products enabling ultra lean operation
  - Low NO_x
  - Increased knock resistance at high loads
  - Integration into production hardware

- Enabling technologies
  - TJI + Boosting



Turbulent Jet Ignition Overview

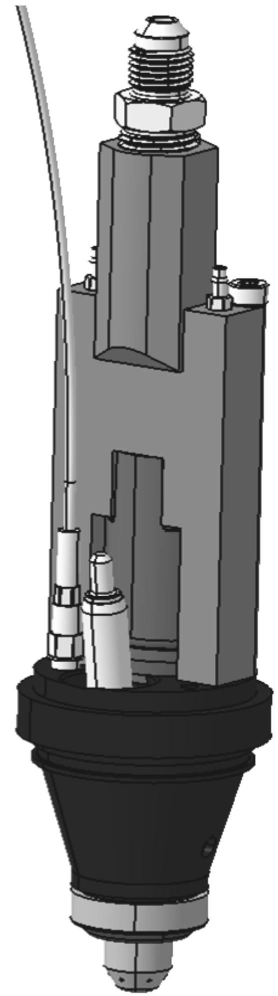
- Auxiliary fueling event enables effective decoupling of pre/main chamber air-fuel ratios
- Thermal efficiency benefit of TJI
  - Ultra-lean operation
  - Reduced throttling losses
  - Reduced knock @ HL
- Boosting can enable map-wide lean/ultra-lean operation
  - Multiple operating strategies/platforms



Objectives/ACE Barriers

- Objectives:
  - Utilize TJI to achieve stated project goals
    - 45% thermal efficiency
    - 30% vehicle drive-cycle fuel economy improvement over baseline
    - Emissions comparable to baseline; minimal modifications to engine
  - Increase understanding of TJI performance sensitivity to design and operating conditions

- Barriers Addressed:
  - (A) Fundamental understanding of an advanced combustion technology
  - (B) Emissions reductions may enable reduced cost emissions controls
  - (C) Develop tools for modeling advanced combustion technology
  - (F) Produce emissions data on an advanced combustion engine
  - (G) Prioritize low cost and ease of integration
  - (H) Provide comparable levels of performance to existing SI engines



Phase-Based Approach

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Optical Engine Testing	Jet velocity as a function of TJI hardware	**Phase 1** *TJI design optimization*
Single Cylinder Metal Engine Testing	Efficiency/emissions as functions of jet velocity	
1-D and 3-D simulations	Validation of experiments, helps drive design optimization	
Boosted Single Cylinder Metal Engine Testing	Fuel injection timing/quantity and spark timing sweeps	**Phase 2** *TJI design validation, operating parameterization*
3-D simulations	Validation of experiments	
Boosted Multi-Cylinder Metal Engine Testing	Mini-map generation provides input to 1-D simulation	**Phase 3** *Map generation and drive cycle simulation*
1-D simulations	Predict TJI vehicle drive cycle fuel economy improvement	

Milestones and Accomplishments Since 2014 AMR

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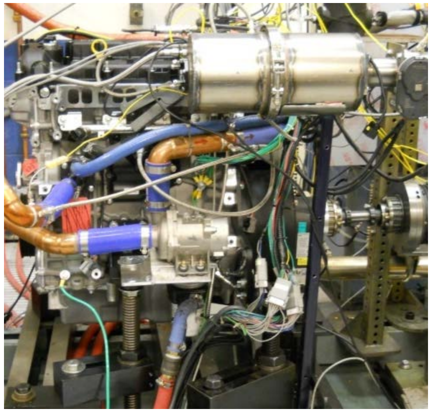
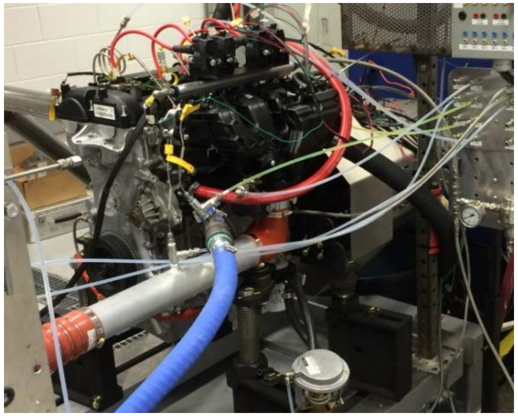
- Completed Phase 2
  - Single cylinder metal engine with addition of boost rig
    - Testing focused on pre-chamber design optimization
    - Development of TJI operating strategy
  - CFD model correlation to experimental data
- Initiated Phase 3
  - Multi-cylinder engine testing
    - Testing focused on producing engine mini-map for drive cycle simulation input

Budget Period	Milestones	Completion Date
1	M1 - Phase 1 Design Work Complete	7/25/2012
1	M2 - Component Procurement Complete	10/30/2012
2	M3 - Single-Cylinder Engine Testing Complete	6/4/2013
2	M4 - Phase 1 Complete	8/10/2013
2	M5 - Boosted Single-Cylinder Engine Shakedown Complete	10/30/2013
2	M6 - Design Optimization Complete	7/15/2014
2	M7 - Phase 2 Complete	11/15/2014
3	M8 - Boosted Multi-Cylinder Engine Build & Shakedown Complete	2/5/2015
3	M9 - Operating Parameter Optimization & Mini-Map Complete	5/1/2015
3	M10 - Project Complete	6/30/2015



Single-cylinder metal engine (Phases 1 and 2)

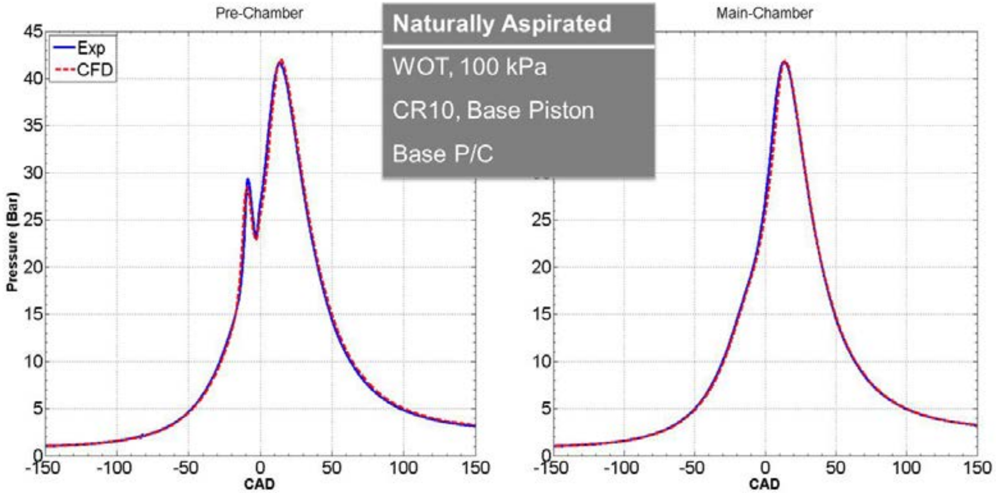


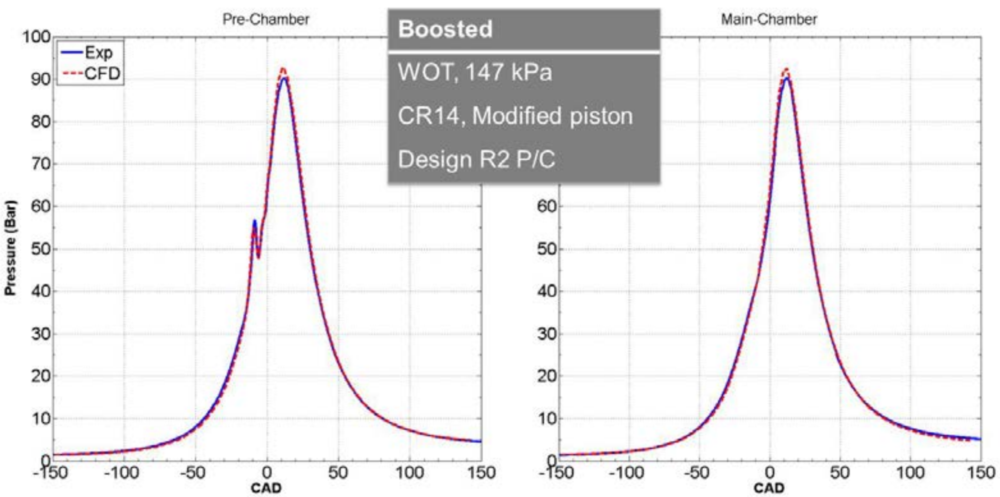
Multi-cylinder metal engine (Phase 3)

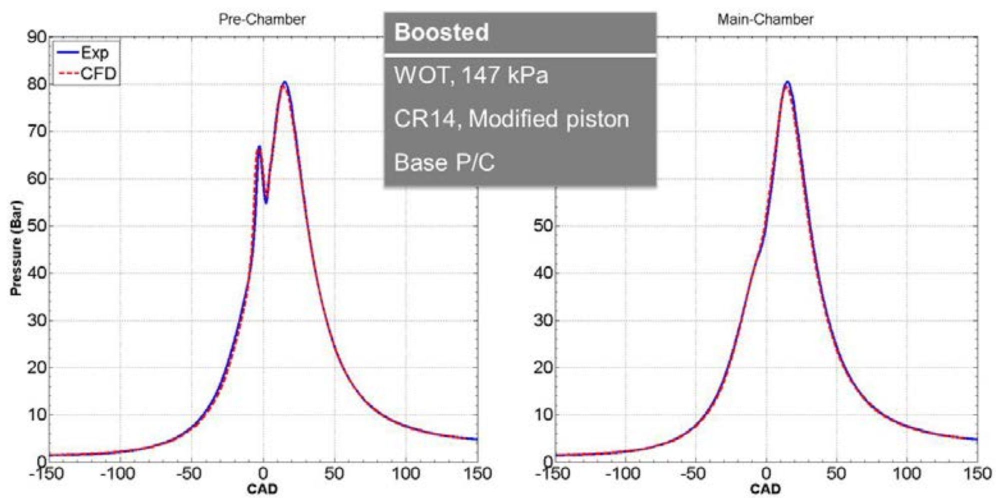
CFD Results: Correlation Status

- CFD correlation achieved
  - Correlated to experimental data from single-cylinder engine
  - Multiple operating conditions
  - Multiple pre-chamber designs

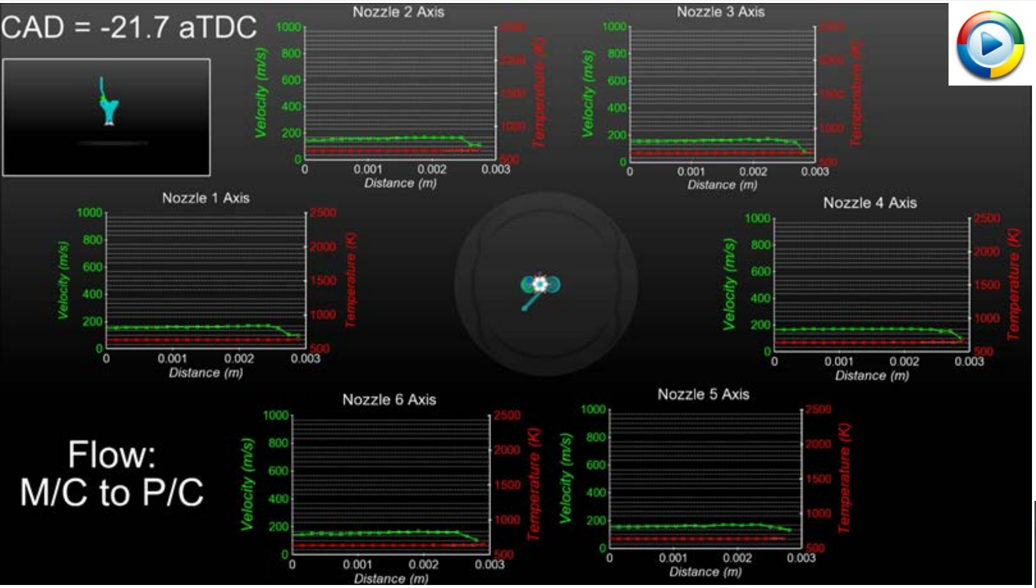
- CFD used as explanatory tool to drive design and operating parameter optimization





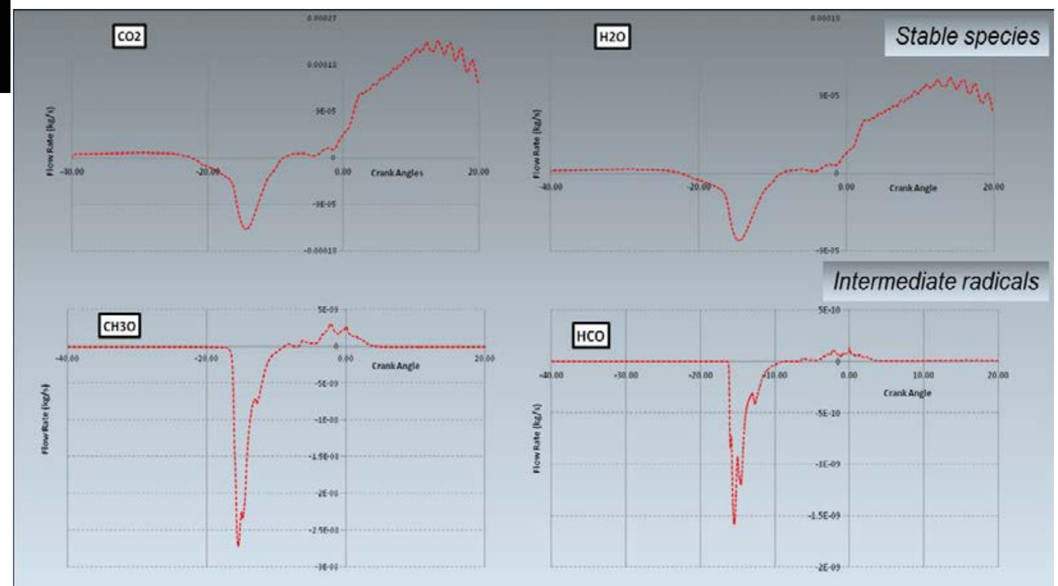


CFD Results: Model Purpose



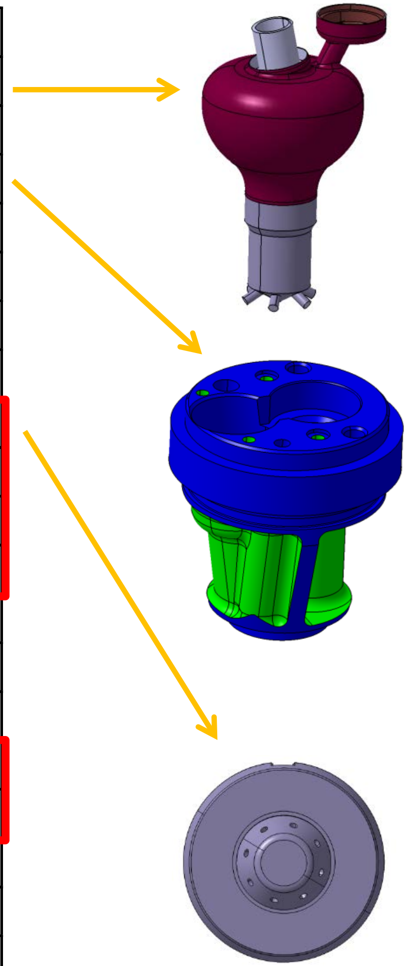
- Model used to explore physical phenomena
  - Internal pre-chamber geometry
  - Spray targeting
  - Jet targeting
  - Jet velocity

- Model used to gain better understanding of thermo-chemical phenomena
  - Radical species content in jets as primary m/c ignition trigger
  - Jet species evolution
    - vs. CAD
    - vs. penetration distance



TJI Design and Operating Parameter Optimization

Optimization	Component	Parameter
design	pre-chamber	volume
design	pre-chamber	component location
design	pre-chamber	active cooling
design	nozzle	volume
design	nozzle	orifice length taper
design	nozzle	orifice angle
design	nozzle	orifice shape
design	nozzle	orifice number
design	nozzle	orifice diameter
design	nozzle	orifice length/diameter
design	nozzle	total orifice area
design	p/c injector	spray angle
design	p/c injector	orifice number
operating	spark	spark timing
operating	p/c injector	fuel quantity
operating	p/c injector	injection angle
operating	p/c injector	injection pressure
operating	p/c injector	number of pulses
operating	p/c injector	pulse split
operating	engine delta P	back pressure



- Design matrix
  - Pre-chamber volume/injector spray interaction
  - Nozzle designs an extension of Phase 1 optimization work
- Operating parameter matrix
  - Determine appropriate fuel quantity in p/c
  - Determine optimal means of delivery

Phase 2 Test Results: Nozzle Design Optimization

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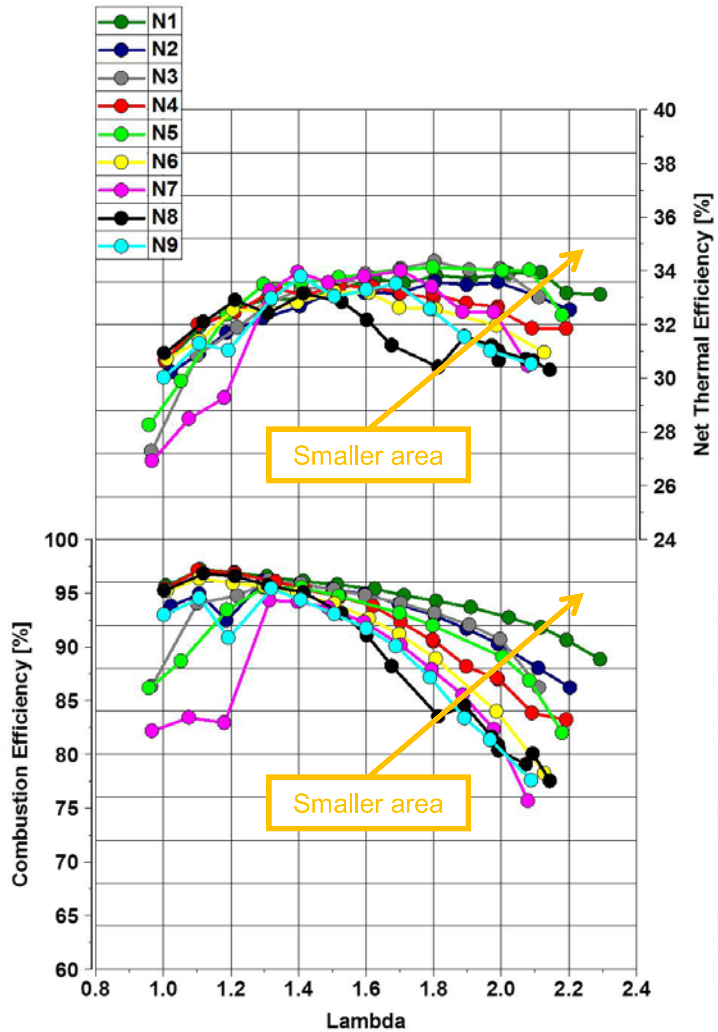
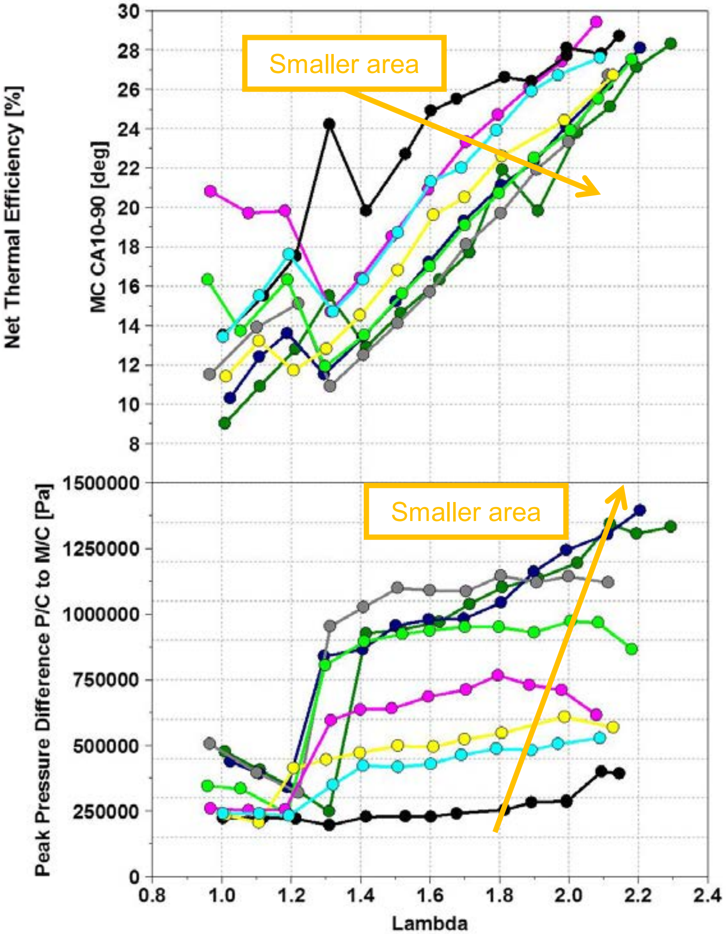
- Low load conditions favor nozzles w/ small orifice area
  - Shorter burn duration
  - Higher TE and CE
- Larger p/c-m/c P difference
  - Driver of jet velocity
  - Greater degree of jet penetration
- Enhanced ignition site distribution → shorter burn duration (data from P1 optical and single-cyl)

Speed: 1500 rpm
IMEPg: 3.9 bar
CR: 14

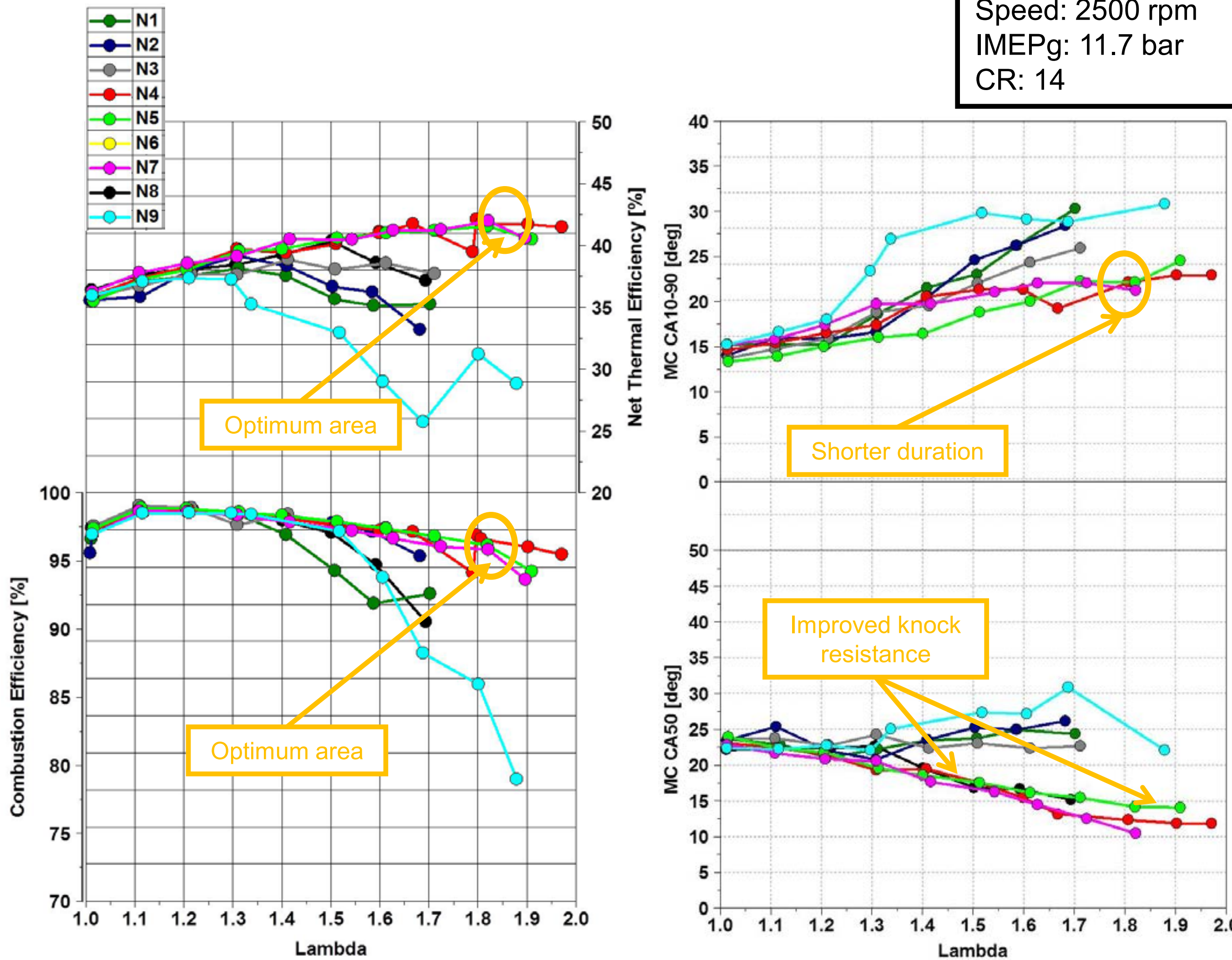




Phase 2 Test Results: Nozzle Design Optimization

- High load conditions favor nozzles w/ optimum orifice area
  - Shorter burn duration
  - Higher TE and CE
- Improved knock resistance → higher TE
  - Enables more optimal combustion phasing
- Nozzle design → high load knock reduction vs. low load fuel economy
  - "Compromise" nozzle design for engine map

Speed: 2500 rpm
IMEPg: 11.7 bar
CR: 14



Phase 2 Test Results: P/C Injection Optimization

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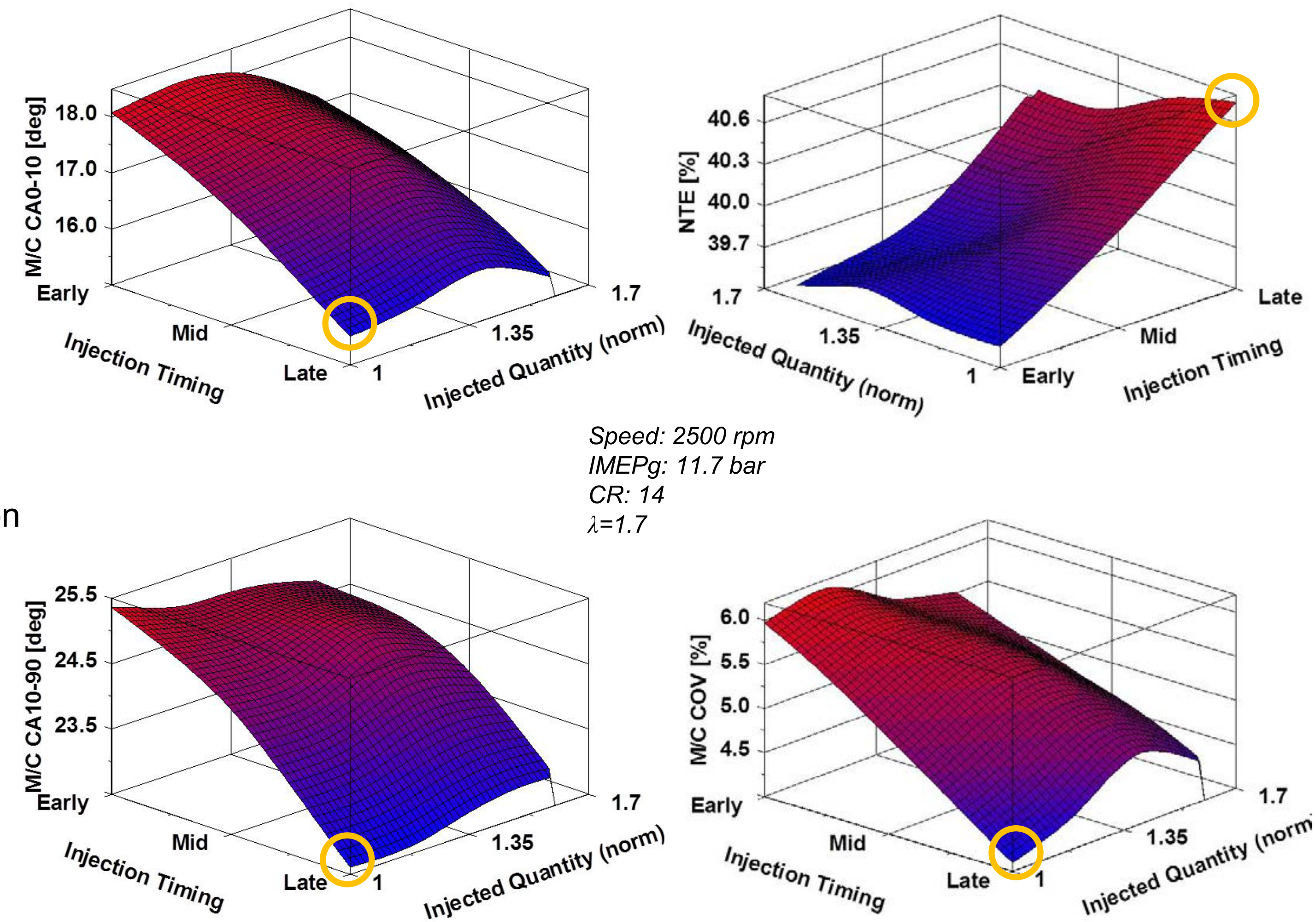
- Late injection angle
  - Reduced m/c COV
  - Reduced m/c CA0-10, CA10-90
  - Increased TE
- Injected fuel quantity
  - Does not contribute to power → efficient utilization
  - Coupled to injection angle
  - Large quantity/early injection
    - Higher m/c COV
    - Slower m/c burn duration
    - Reduced TE



Phase 2 CFD Results: P/C Injection Optimization

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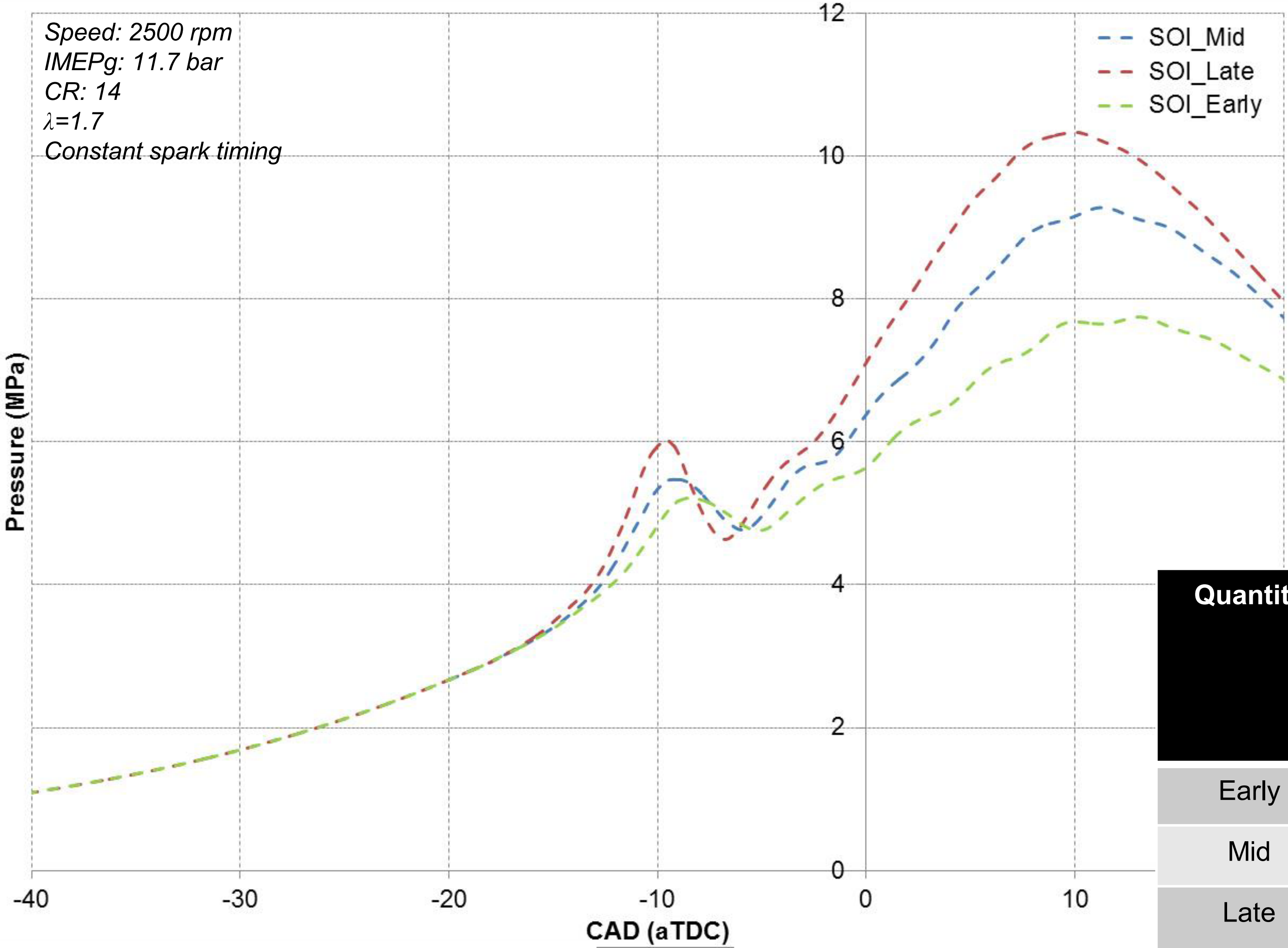
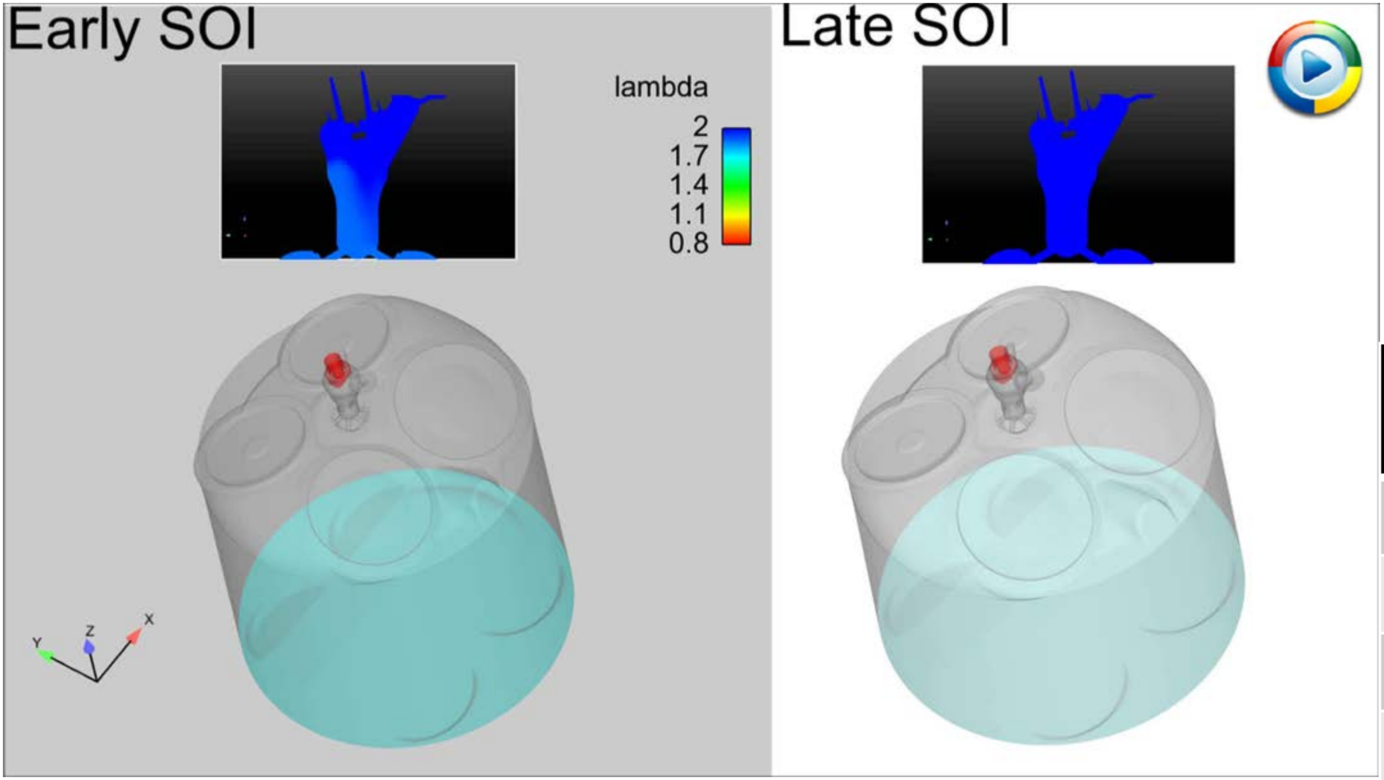


Case	Lambda p/c overall @ ST	Lambda @ Spark plug
Early	1.07	>1.2
Mid	0.98	1.1
Late	0.92	0.95

Quantity	Fuel efflux mass before ST (mg)	Fuel efflux mass during jet process (mg)	Incomplete products (mg)
Early	0.11	0.29	0.05
Mid	0.03	0.29	0.09
Late	0	0.35	0.14

Phase 2 CFD Results: P/C Injection Optimization

Speed: 2500 rpm
IMEPg: 11.7 bar
CR: 14
λ=1.7
Constant spark timing



Energy Release	Early	Mid	Late
10%	-0.46	-2.85	-4.33
50%	11.31	6.97	4.37
90%	34	19.07	14.01

Duration	Early	Mid	Late
0-10%	17.56	15.17	13.69
10-50%	11.77	9.82	8.7
50-90%	22.69	12.1	9.64
10-90%	34.46	21.92	18.34

Phase 3 Test Results: BSFC

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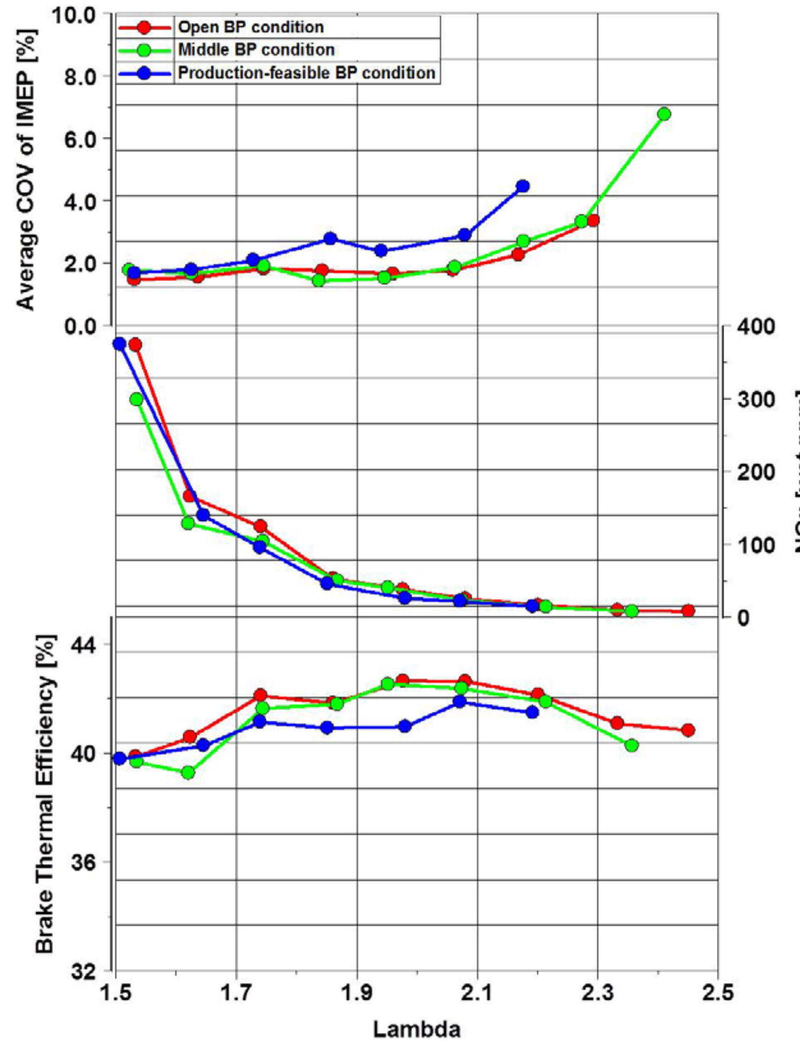
- Preliminary multi-cylinder engine results demonstrate reductions in BSFC with TJI vs. multiple baseline engines
  - 10-15% average preliminary BSFC reduction with TJI vs. comparable size NA engines at various common drive-cycle speed/load points

- Future work
  - Analyze map-wide operating strategy
  - Proper drive-cycle comparison
  - Evaluate downsizing strategies

		2.4L NA PFI	2.4L NA DI	2.4L TJI		2.4L TJI vs. 2.4L NA PFI	2.4L TJI vs. 2.4L NA DI
Speed	BMEP	BSFC	BSFC	BSFC	Lambda	BSFC Reduction	BSFC Reduction
rpm	bar	g/kWhr	g/kWhr	g/kWhr			
750	3	279	303	258	1.7	7%	15%
1500	3	271	286	250	2	8%	13%
1500	6	237	242	206	2	13%	15%
2000	3	276	285	258	1.7	7%	10%
2000	4.5	254	260	221	1.6	13%	15%
2000	6	239	236	207	2.3	14%	12%
2000	8	241	230	194	2.1	19%	16%
2500	3	285	287	259	2	9%	10%
2500	4	260	262	239	1.7	8%	9%
2500	6	243	238	215	2	12%	10%

Phase 3 Test Results: BTE

- Preliminary multi-cylinder engine results demonstrate similar engine performance behavior to single-cylinder engine
  - Minimal cylinder-to-cylinder variation
- Brake Thermal Efficiency values >41% @ 2.0<λ<2.1
  - Design optimization
    - Engine map “compromise” nozzle design
  - Operating strategy optimization
- Future work
  - Further operating strategy refinement
  - Peak efficiency point determination



Speed: 2500 rpm
BMEP: 10bar
CR: 14

Response to Previous Year Reviewers' Comments

- **Multiple comments concerning realistic boost system losses**
  - "…essential to consider realistic losses for the boost system,…a low exhaust temperature may require a difficult boost system [solution]…"
  - "…turbocharger emulation was [needed] in thermal efficiency."
  - RESPONSE: External boost rig is used for boosting in this project due to lack of scope for turbocharger matching. High back pressure conditions are used to emulate thermal efficiency trade-off with high boost capability. Parasitic losses will be researched and applied to BTE results from Phase 3 multi-cylinder engine testing. Low temp boost solution for optimal coupling with TJI will be investigated in follow-on project.
- **Multiple comments concerning durability of pre-chamber injectors and TJI nozzle**
  - "…limitations associated with this approach…included durability (to coking/clogging)..."
  - "…the project's next steps needed to address durability (to coking/clogging)…"
  - RESPONSE: Production-level durability is beyond the scope of the current project. However, p/c injector optimization activities (MPT/Delphi) included significant considerations for injector clogging, as well as proof-of-concept tests. Analyses included: 1) gravimetric analysis of deposits, 2) injector tip temperature measurement, and 3) CFD fuel spray and vaporization analysis. Through several hundred hours of TJI operation, both on current project and others, there has been no evidence of TJI nozzle plugging.

Collaborations

- **Ford Motor Company** – Project Partner
  - Donated engine hardware, offered technical advice, are participating in data sharing
- **Delphi Corporation** – Project Subcontractor
  - Supplied pre-chamber fuel injectors and conducted CFD analysis on fuel injection characteristics, offered technical advice
- **Spectral Energies LLC** – Project Subcontractor
  - Acquired optical engine data, contributed to post-processing
- **University Collaboration**
  - Engaged multiple universities concerning further TJI investigation

Upcoming Project Work and Challenges

Key Challenges

- Challenge: Achieving 30% vehicle drive-cycle fuel economy improvement with TJI
  - Multi-cylinder TJI engine testing is necessary to determine accurate brake specific fuel consumption
- Challenge: Optimization of CR/knock reduction/peak efficiency/degree of downsizing
  - System-level optimization of engine geometry/operating parameters to maximize efficiency according to preferred operation

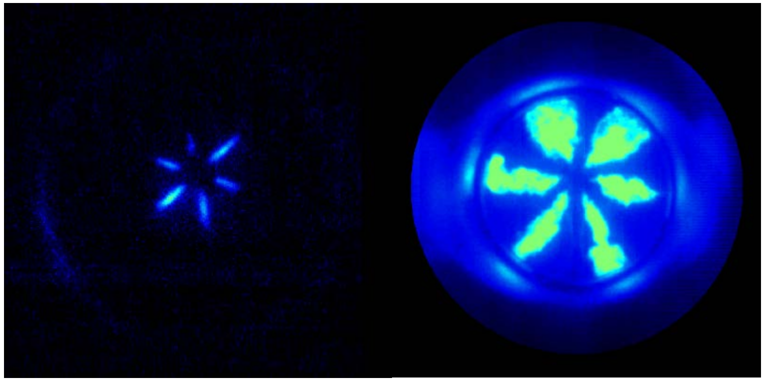
Future Work

- Phase 3:
  - Complete multi-cylinder engine testing
    - Mini-map generation
  - Complete 1D vehicle drive-cycle analysis
    - System-level analysis of TJI operating strategy across engine map

Summary of Work Since 2014 AMR

- Phase 2 pre-chamber design optimization and operating strategy development completed
  - Significant engine performance benefits from this effort
    - Peak efficiency (NTE>45%)
  - Correlated CFD model as explanatory tool
    - Empirical design optimization
    - Empirical operating strategy refinement
- Phase 3 multi-cylinder engine testing ongoing
  - Preliminary results demonstrate good translation of TJI engine performance from single-cylinder engine

Project Goal	Phase Accomplished	Status
Minimal modifications to engine design	Phase 1	achieved ✓
45% peak thermal efficiency	Phase 2	exceeded ✓
Emissions comparable to baseline	Phase 3	work ongoing
30% vehicle drive-cycle fuel economy improvement over baseline	Phase 3	work ongoing



MPT would like to acknowledge DOE Vehicle Technologies Office for funding this work.

Thank you for your attention

Technical Back Up Slides

Turbulent Jet Ignition Overview

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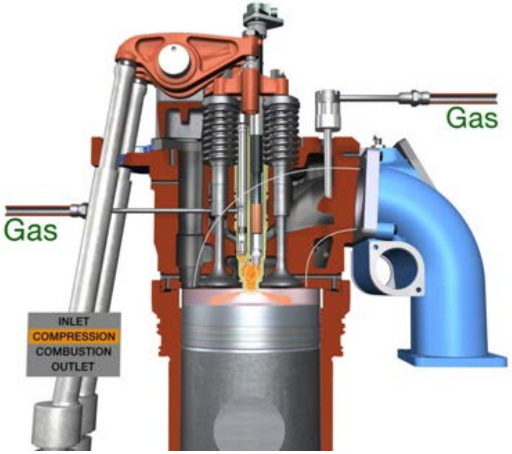
- Pre-chamber combustion concepts are not new
  - Ricardo "comet combustion pre-chamber" – 1920s
  - Applied to SI engines as a lean combustion enabling technology
    - Investigated by many OEMs – Honda, VW, etc.
  - Currently in production in large-bore CNG gensets

- TJI is an innovative approach to the pre-chamber concept
  - Auxiliary pre-chamber fueling using prototype low-flow DI injector
    - Enables spray targeting, precise metering
  - Small volume pre-chamber = small auxiliary fuel requirement
  - Small nozzle orifice diameter promotes flame quenching
    - Jet penetration into main chamber before re-ignition
  - Multiple orifices result in distributed ignition



Wartsila SG


Turbulent jet igniter

Phase 1 Analysis of Optical and Metal Engine Data

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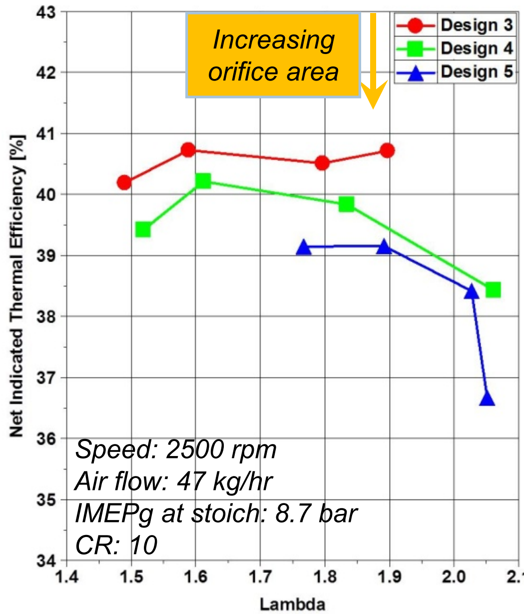
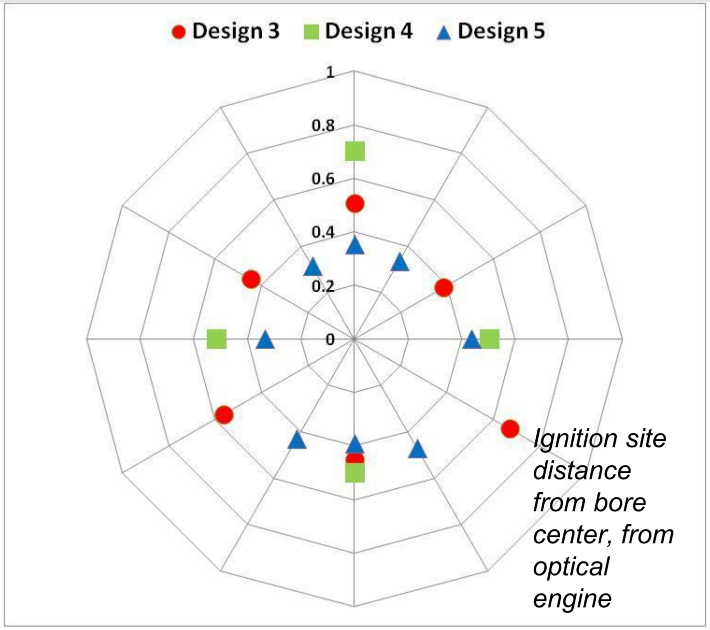
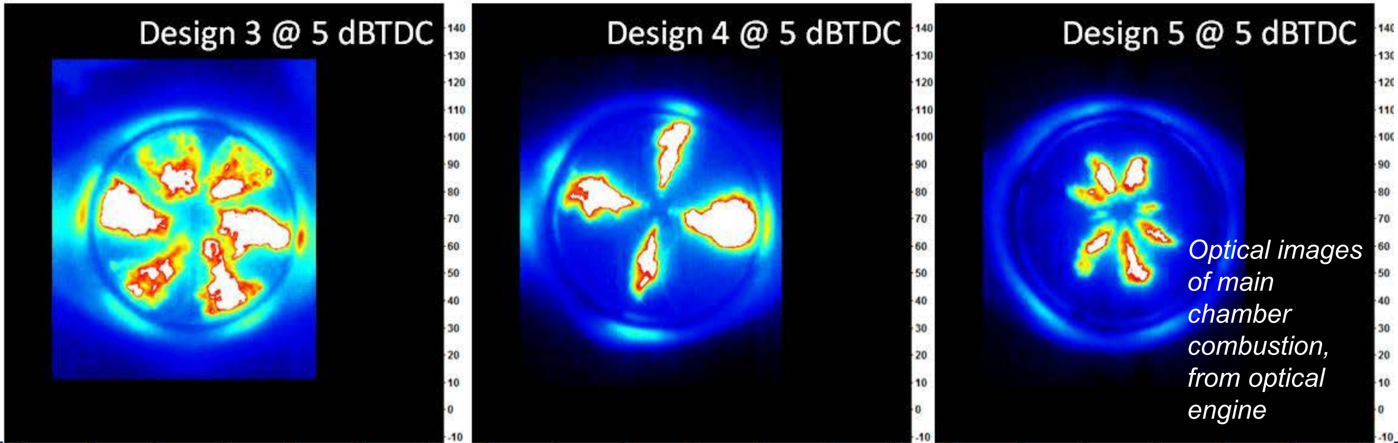
- Small orifice area → short burn duration → high net thermal efficiency
- Short burn duration is associated with:
  - Enhanced distribution of ignition sites
  - Short flame travel distance
- **Conclusion:** Jet velocity and ignition site distribution targeting through nozzle geometry to optimize NTE





Ignition site distance from bore center, from optical engine



Optical images of main chamber combustion, from optical engine

Phase 2A Engine Results: Thermal Efficiency

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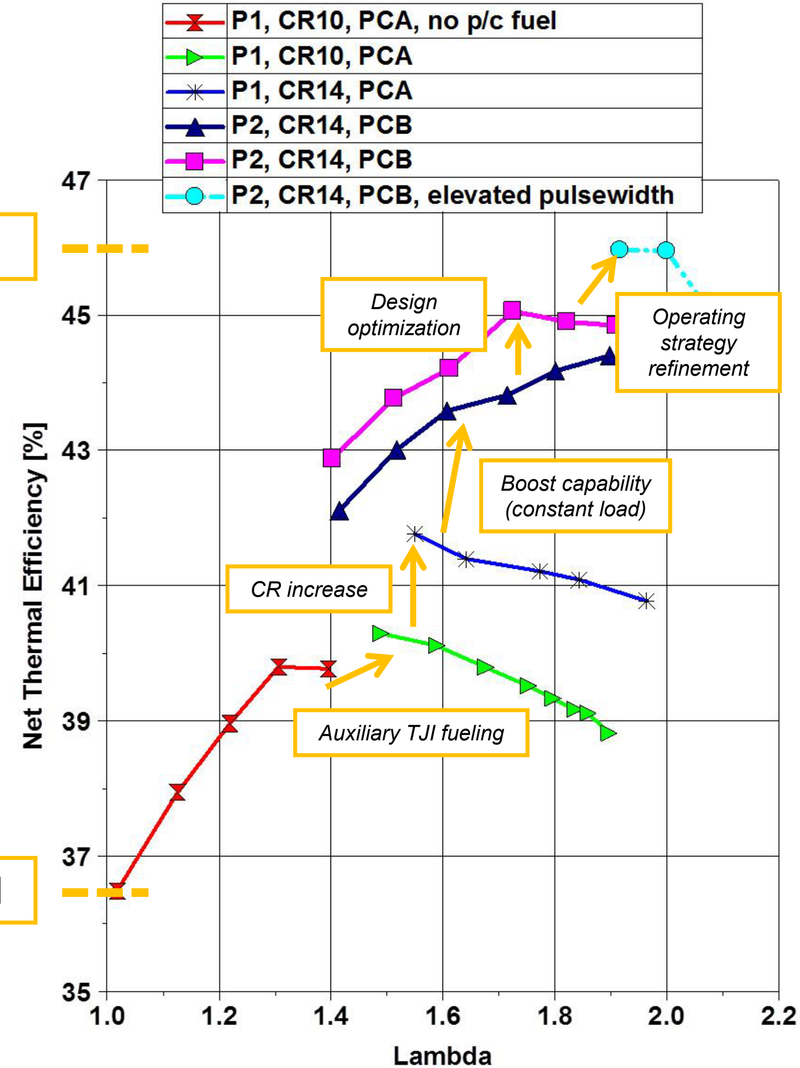
- Promising p/c and nozzle designs tested further
  - Preliminary operating strategy investigation
- Data suggests TJI can exceed 45% net thermal efficiency
  - Relationship between added p/c fuel, jet strength, and m/c HRR
  - Primary project objective exceeded

TJI peak efficiency to-date

Engine: 0.6L single-cylinder engine w/ TJI
Speed: 2500 rpm
Phase 1 IMEPg: 8.7 bar, WOT, airflow-limited
Phase 2 IMEPg: 11.7 bar, WOT, boosted

Base engine efficiency @ λ=1



Phase 2A Engine Results: Combustion Stability

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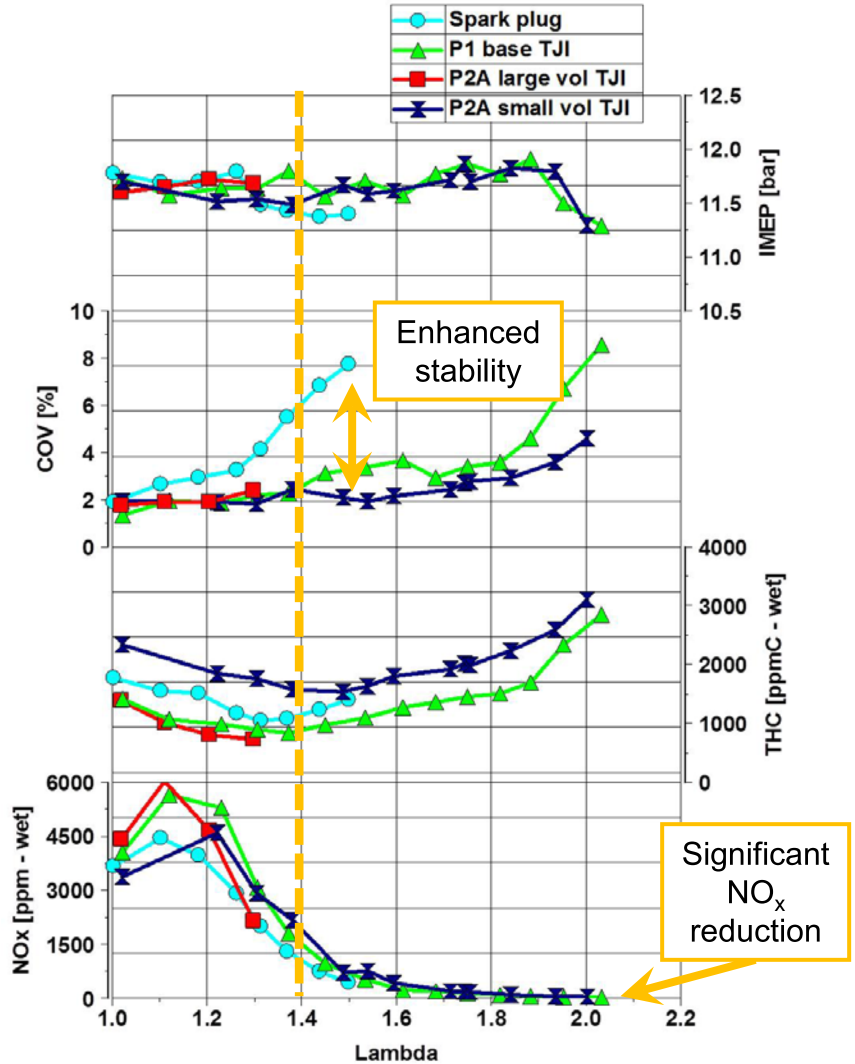
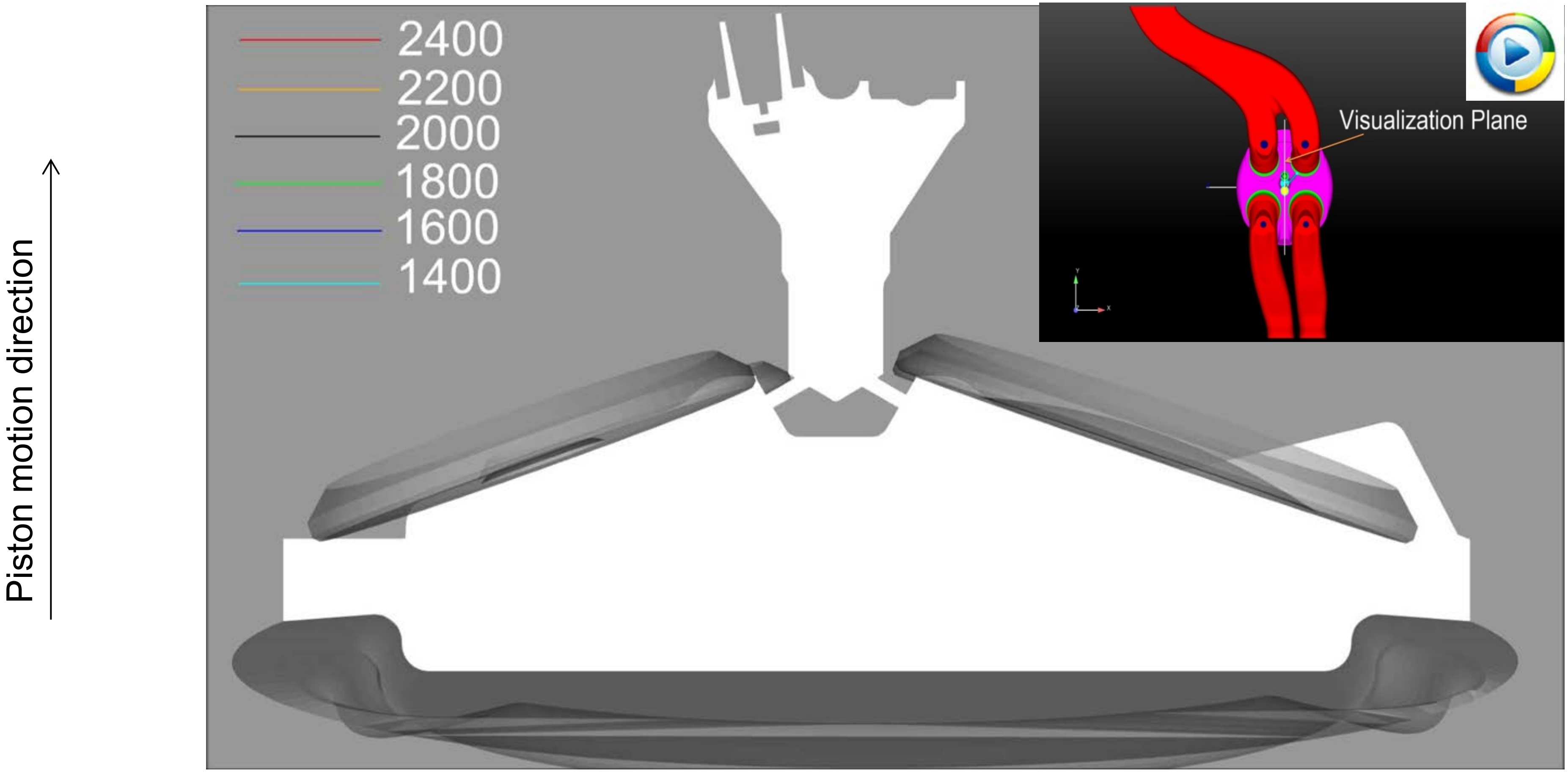
- Blended pre-chamber operating strategy
  - No auxiliary fuel: λ < 1.4
  - Auxiliary fuel injection: λ > 1.4

- Data demonstrates superior combustion stability with TJI vs. base spark, even in near-lean region
  - Distributed ignition
  - Enhanced ignition energy

Speed: 2500 rpm
IMEPg: 11.7 bar
CR: 14



CFD Results: Flame Quenching



High temperature boundaries are confined within the pre-chamber volume while main chamber combustion proceeds at lower temperature