Flex Fuel Optimized SI and HCCI Engine

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Michigan State University

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Project ID #: ACE021

Overview

Timeline

Phase 1: 10/01/09 ~ 05/31/10 ✓
Phase 2: 06/01/10 ~ 05/31/11 ✓
Phase 3: 06/01/11 ~ 03/31/12
Phase 4: 04/01/12 ~ 09/30/12

Phase 3: 80% complete by 03/26/12

Budget

Total Project Funding (all phases)
- DOE $1,401,299
- Recipient $ 584,240

DOE funding obligated/budgeted
- FY 10 $444,172/$444,172
- FY 11 $517,638/$517,638
- FY 12 $280,463/$439,489

Recipient (up to date):

Chrysler: $262.105K (labor, prototype engine and parts)
MSU: $123K (in-kind)

Barriers

- Lack of modeling capability for combustion and emission control: Development of a control oriented (real-time) hybrid combustion model for model-based mode transition control between SI and HCCI combustions.

- Lack of effective engine control: Development of a model-based SI and HCCI mode transition control strategy for smooth combustion mode transition using iterative learning control.

- Cost (high HCCI engine cost): Development of a cost effective and reliable dual combustion mode engine (multi-cylinder and flex fuel) using cost effective actuating system (two-step valves and electrical cam phasing system).

Partners

- MSU (project lead)
- Chrysler Group LLC (industrial partner)
- Delphi (cylinder head)
- Ricardo (modeling)

Objectives

Demonstrate an SI and HCCI dual-mode combustion engine (multi-cylinder), that is commercially viable, for a blend of gasoline and E85.

FY11/FY12 Objectives (Review Period):

a)Finalize the combustion mode transition control algorithm through the hardware-in-the-loop simulations.

b)Complete the valve-train design with the two-step lift and electrical VVT for both optical and metal engines.

c)Complete the control strategy development for the electrical VVT system

d)Complete the fabrication and integration of the optical engine with the target valve-train and study the combustion mode transition for the target engine through combustion visualization.

e)Completed the prototype engine control system (for both optical and four-cylinder engines) capable of sampling combustion information every crank

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Milestones

FY11/FY12 Milestones:

| Month/Year	Milestone or Go/No-Go Decision
March-11 (✓)	Milestone: Completed optical engine tests with updated engine head (two-step valve and electrical phasing)
May-11 (✓)	Milestone: Completed engine system integration (two-step valve and electrical phasing)
March-12 (✓)	Milestone: Completed HCCI mode transition control strategy development

Approach

Use engine modeling, model-based combustion control, and engine experiments to develop a smooth SI and HCCI transitions

- ❑ <u>Control Oriented (real-time) engine modeling:</u> Develop a control oriented hybrid (spark assistant) combustion model for model-based combustion mode transition control.

- ❑ <u>Model-based dynamic engine control</u>: Use a model based iterative learning control strategy (stead-state optimized control parameters are NOT optimal during transitional operation).

- ❑ <u>Use production feasible hardware:</u> Actuating and sensing hardware must be low "cost" and HCCI capable to be production feasible

- ❑ <u>Optical and metal engine experiments</u>: Provide physics based understanding (optical) and durability needed for calibration and validation of engine model (metal)

- ❑ <u>Technology transfer</u>: work with our industrial partner, Chrysler Group LLC, during the project period to ensure smooth technology transfer to industry.

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Technical Accomplishments

## a) <u>Finalized mode transition control with HIL validation</u>

- A five-cycle mode transition control strategy was developed and validated in the HIL simulation environment

- The HIL simulation environment was developed for the SI-HCCI engine equipped with two-step valves and electrical VVT.

- Iterative learning and LQ tracking are used to during the mode transition

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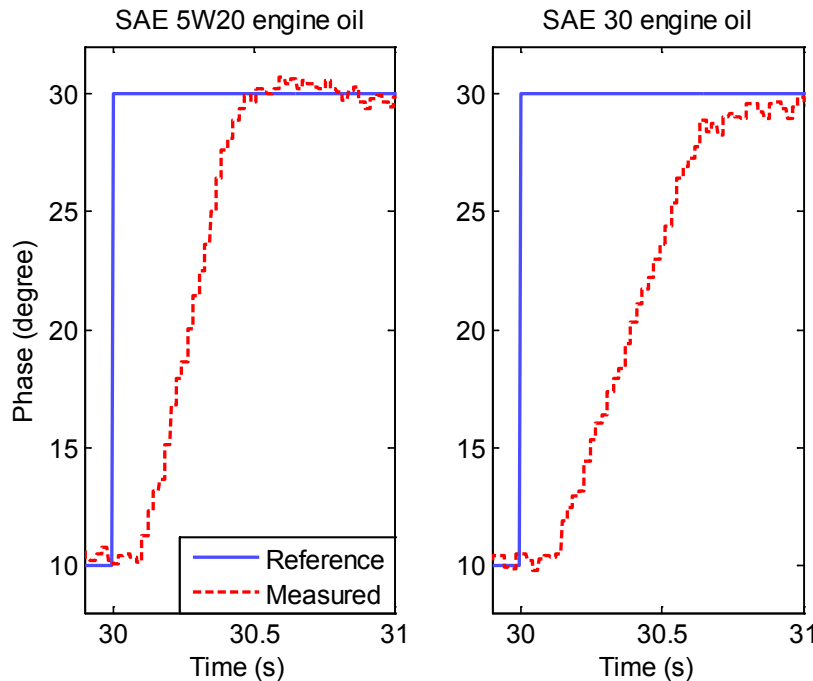UNIVERSITY
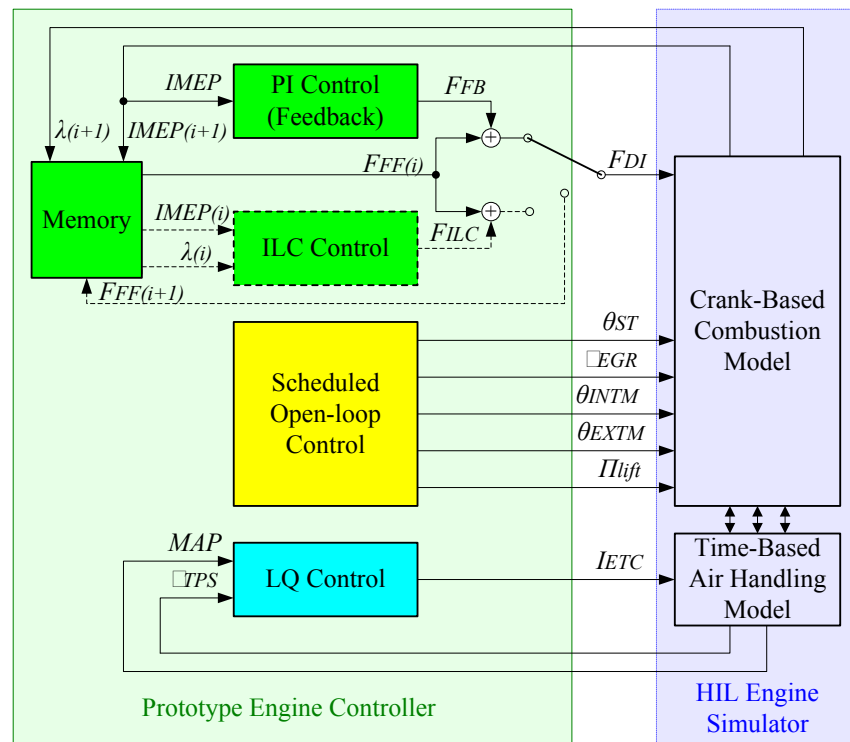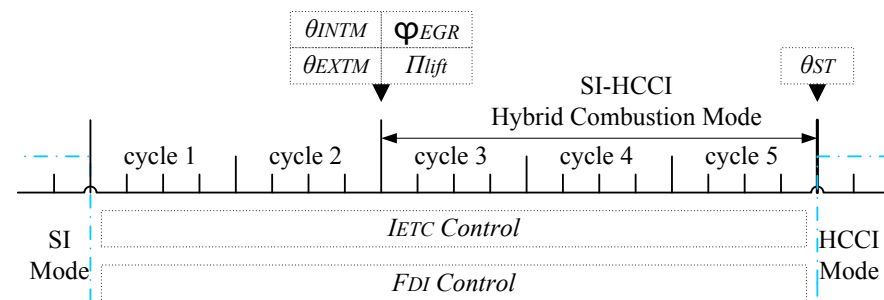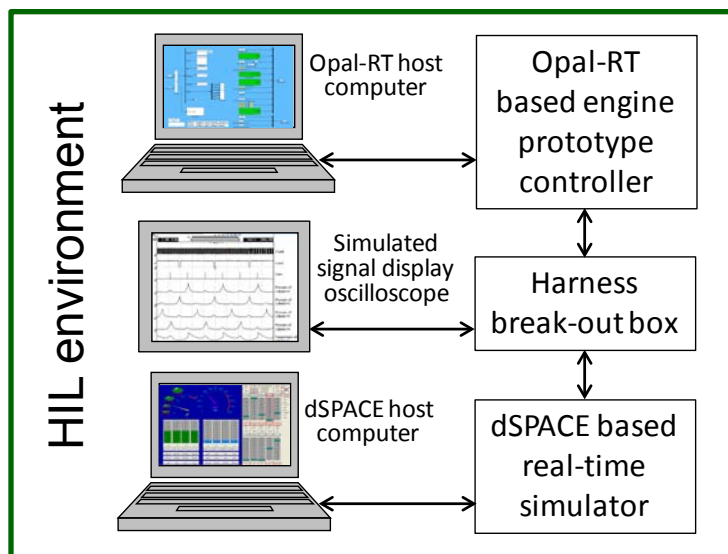
Technical Accomplishments

LQ MAP tracking

❑ Throttle current is regulated in a non-monotonic increment pattern

❑ Throttle angle responses in the similar pattern to the throttle current, but with a small phase lag

❑ Engine MAP tracks the desired reference trace with slight oscillation

❑ Air-to-fuel ratio can be regulated within the desired range

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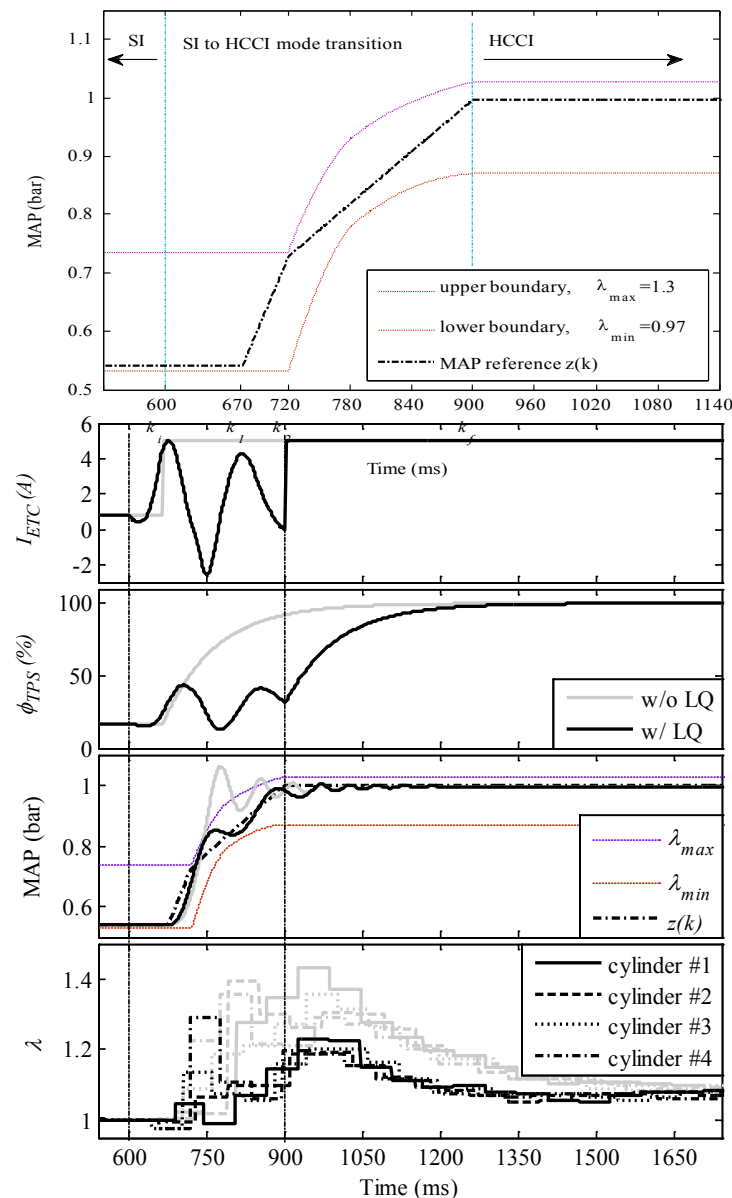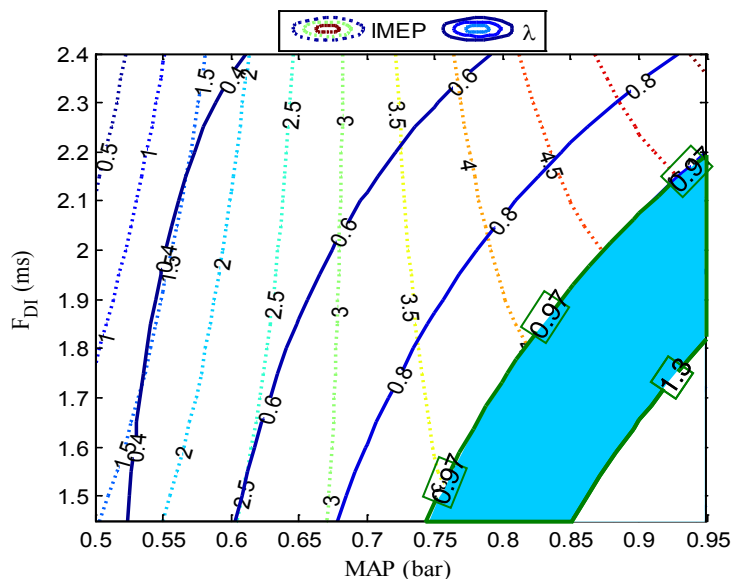
Technical Accomplishments

b) Completed electrical VVT control

- ❑ An EVVT test bench was constructed for the control strategy development of closed loop cam phasing tracking

- ❑ Fast response: 25 degree phasing within 3 engine cycles at 1500 RPM

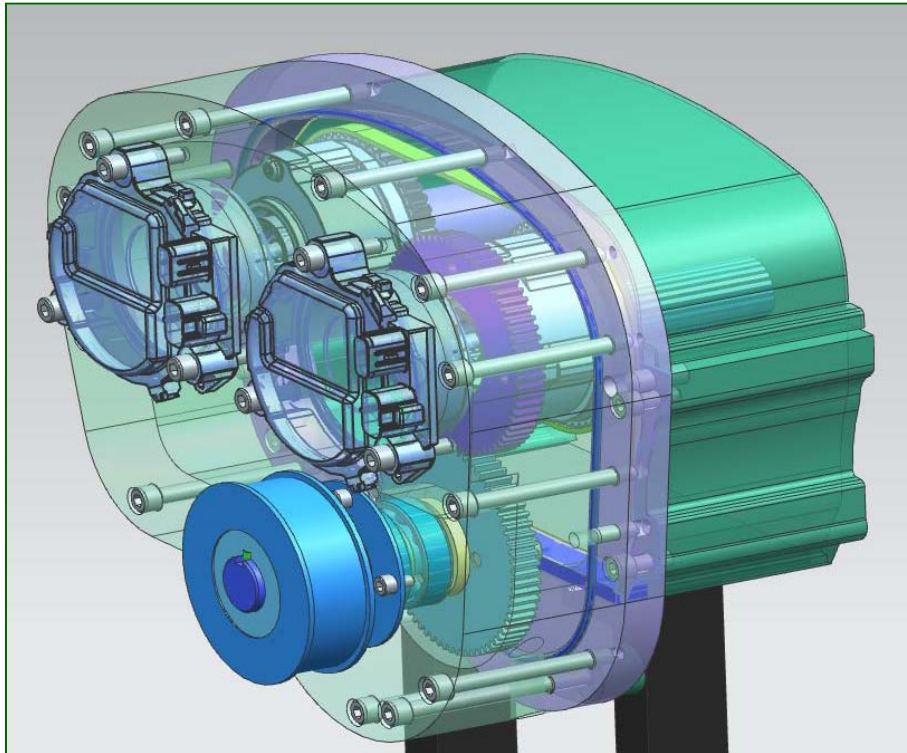- ❑ Oil viscosity impacts the transient (tracking) response time significantly

Controller performance evaluation - trajectory following @1500rpm

SAE 5W20 engine oil

SAE 30 engine oil

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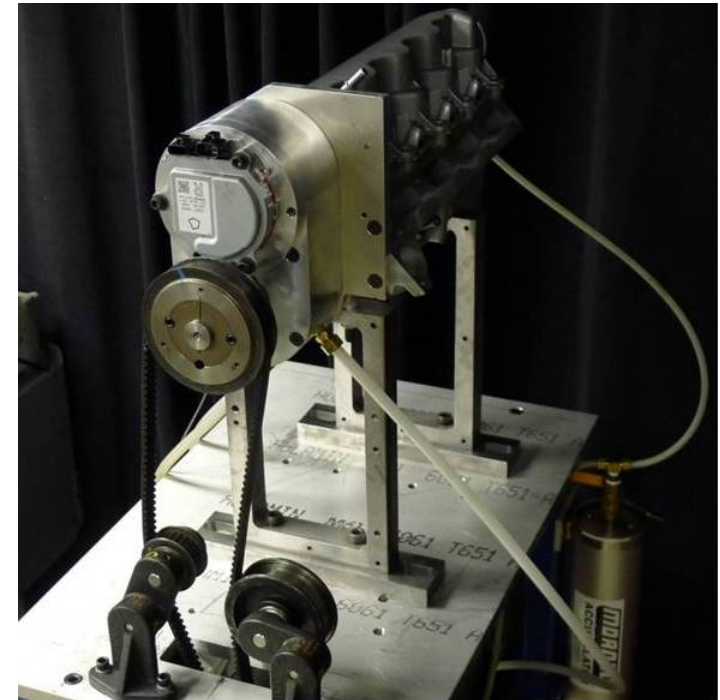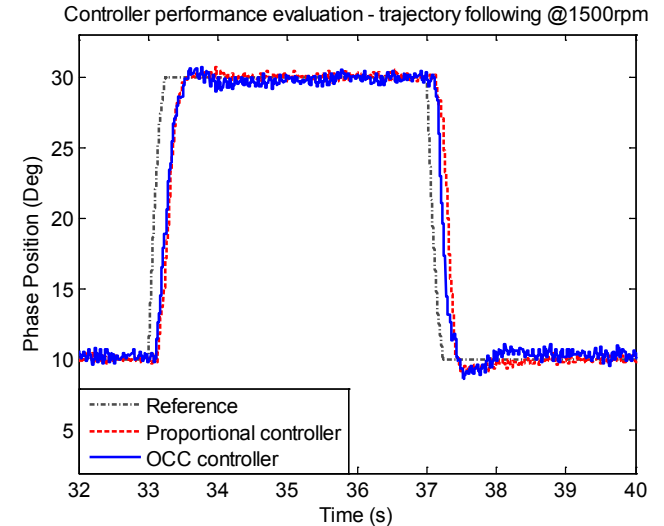
Technical Accomplishments

c) Engine system development

- ❑ Completed EVVT integration to both optical and multi-cylinders.
- ❑ Completed two-step valve integration

Multi-cylinder EVVT integration

Optical Engine EVVT integration
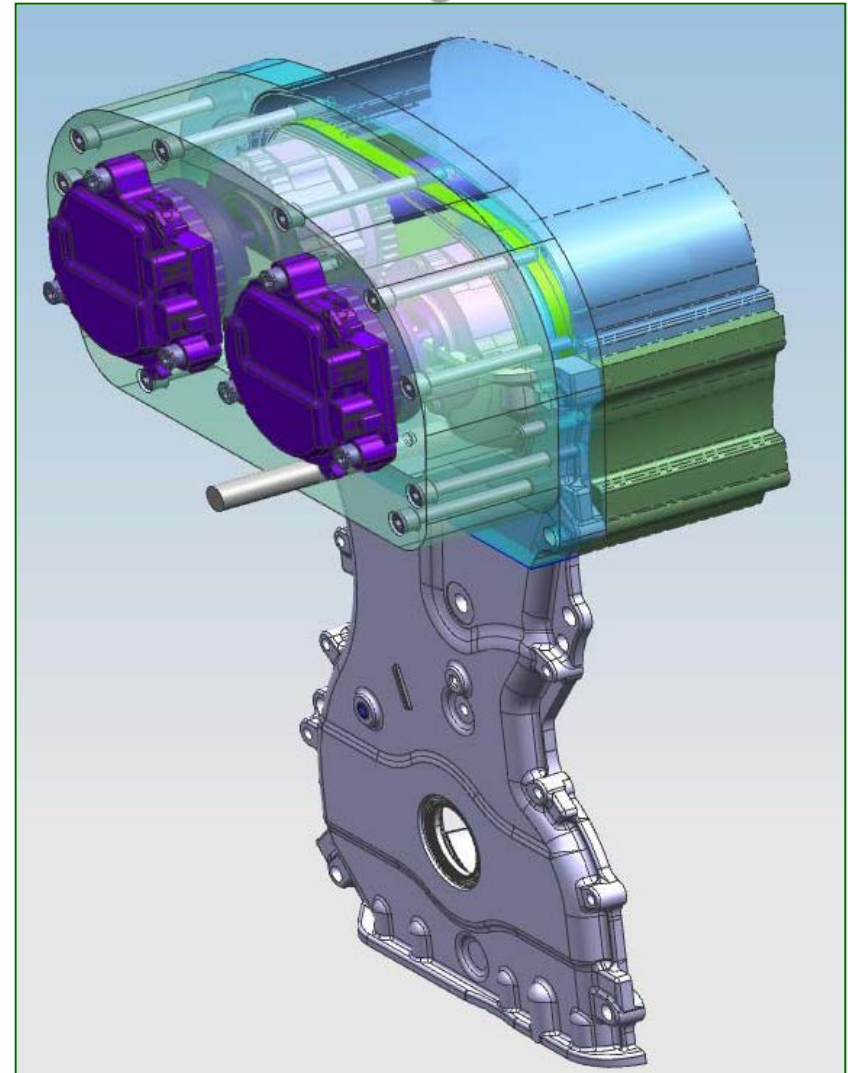
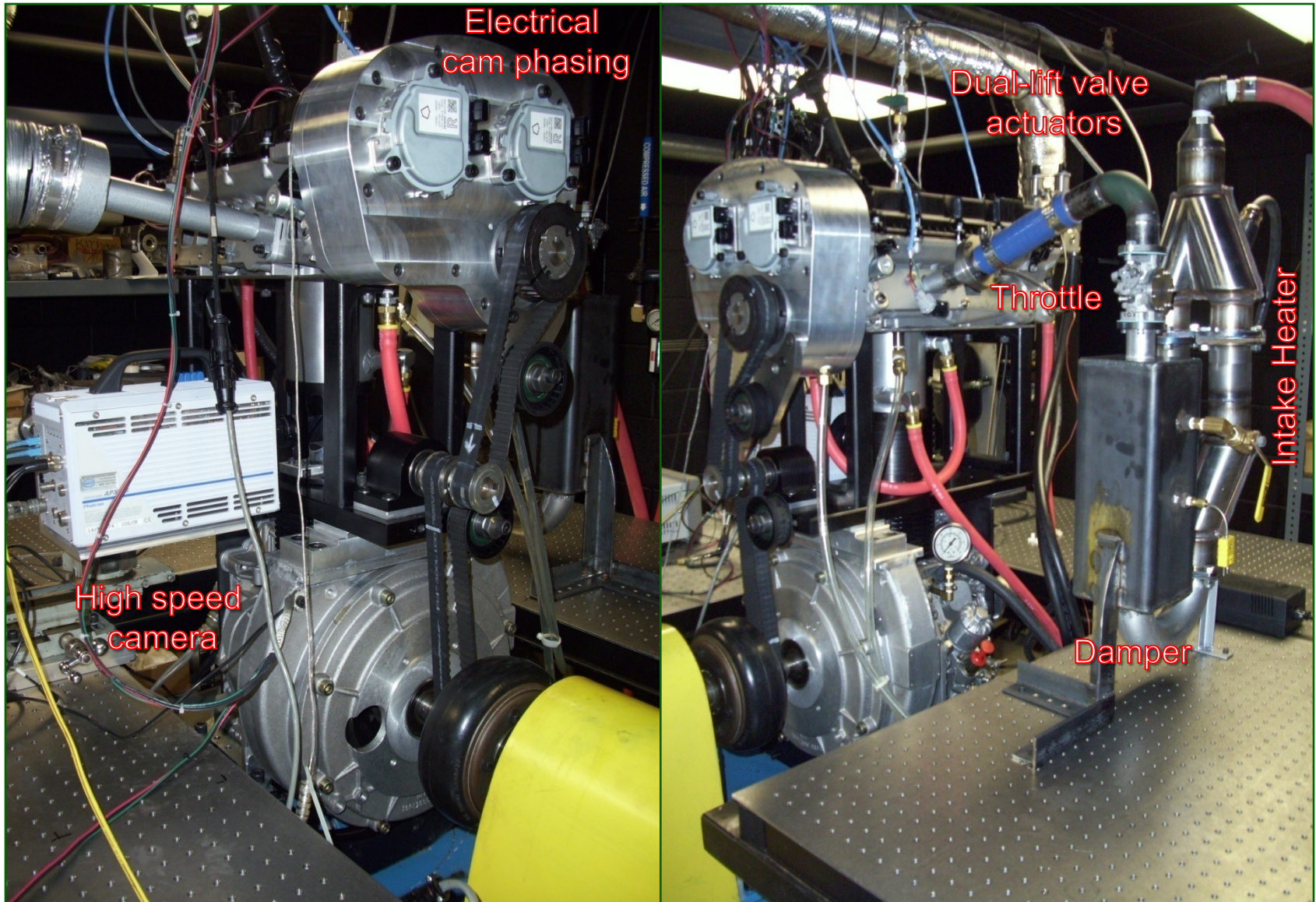# Technical Accomplishments

Optical Engine Integration

- ❑ 0.5L cylinder
- ❑ Direct injection (10MPa)
- ❑ Dual-lift intake/exhaust valves with dual-cam profiles
- ❑ Fast electrical cam phasing ($\pm$40 degrees)
- ❑ Fast electronic throttle
- ❑ Heated engine head and cylinder
- ❑ Heated charge air with closed loop temperature control
- ❑ Key engine sensors for closed loop control: in-cylinder pressure and ionization, AFR, manifold pressure and temperature, mass-air-flow, dual cam positions, etc.

Engine Controller capable of sampling crank-based pressure signal

Technical Accomplishments

Optical Engine

Electrical cam phasing

Dual-lift valve actuators

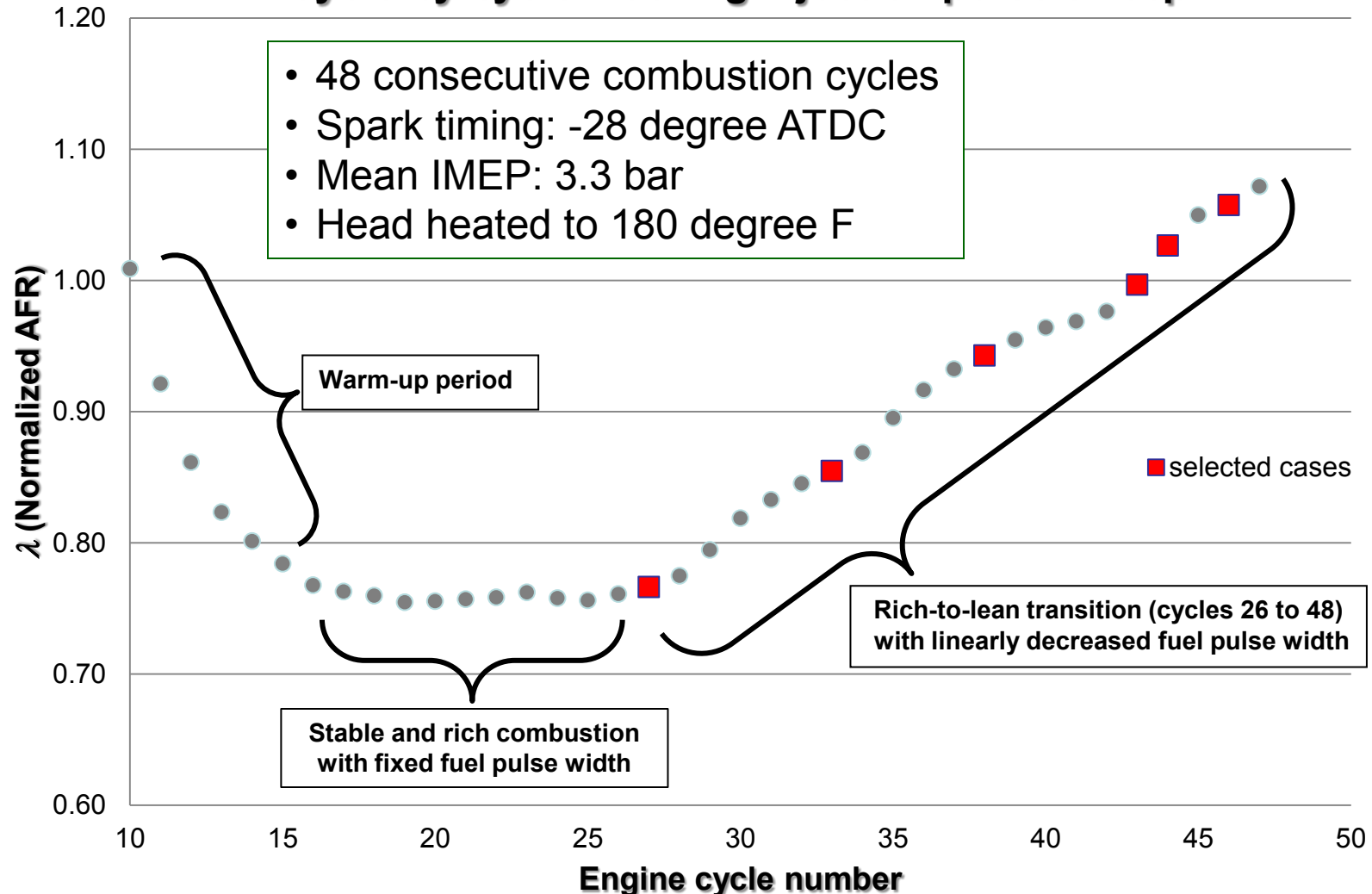Throttle

Intake Heater

High speed camera

Damper
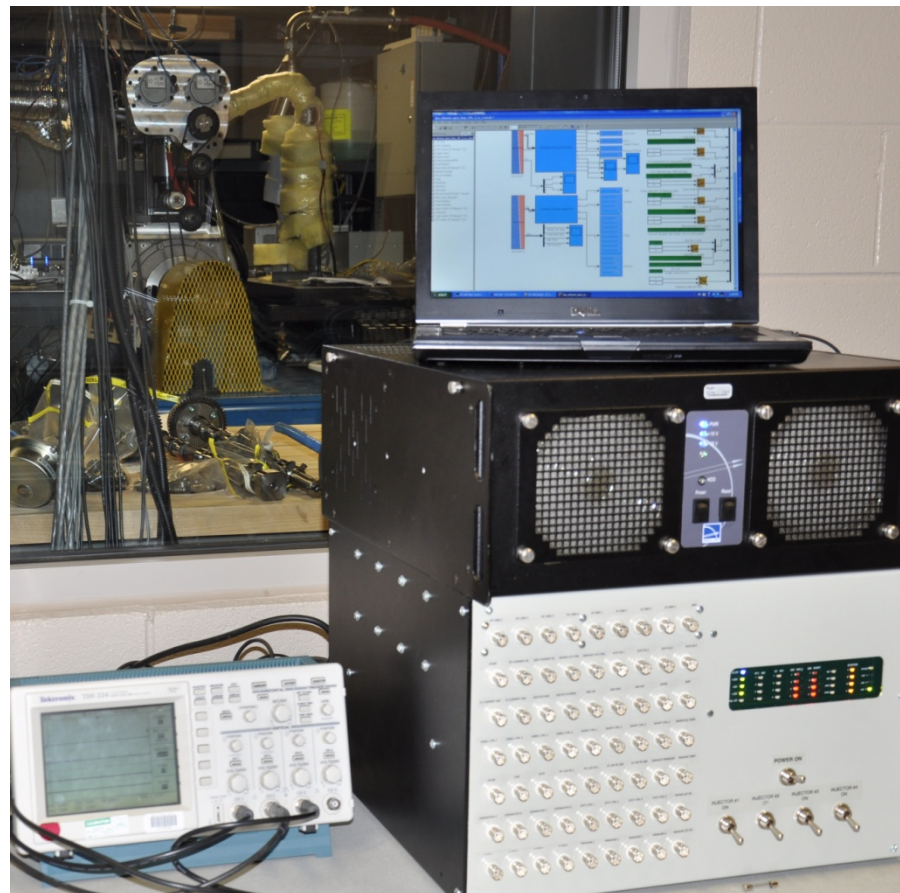
Technical Accomplishments
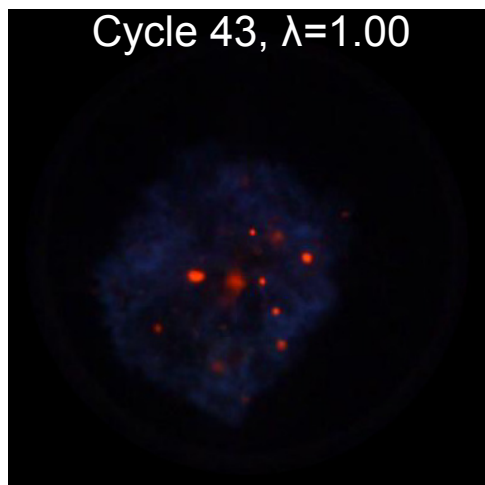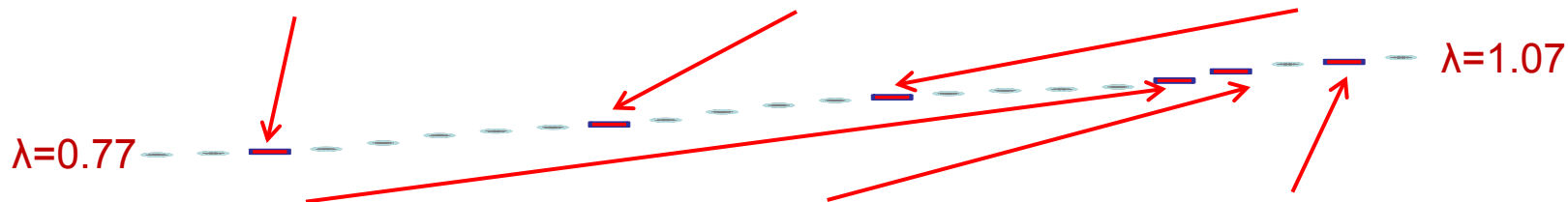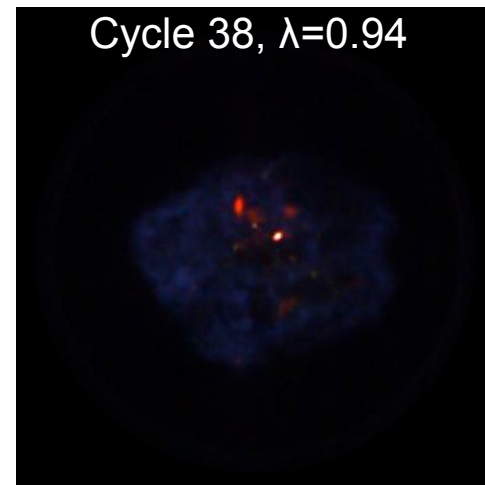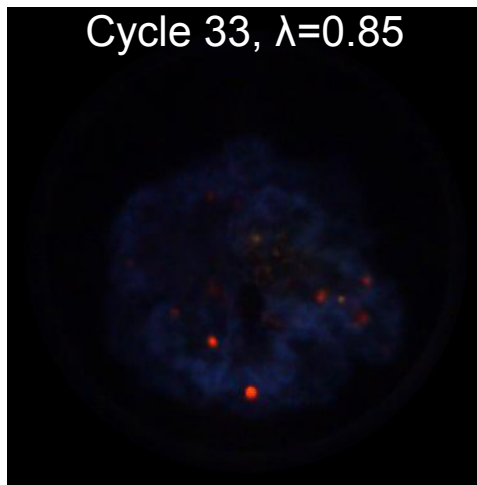
d) Optical engine combustion tests
Rich-lean SI transient combustion

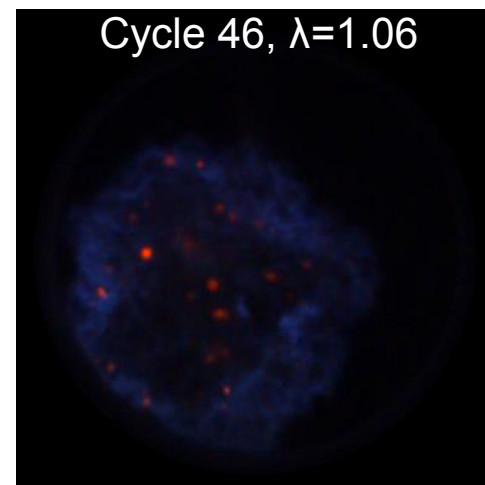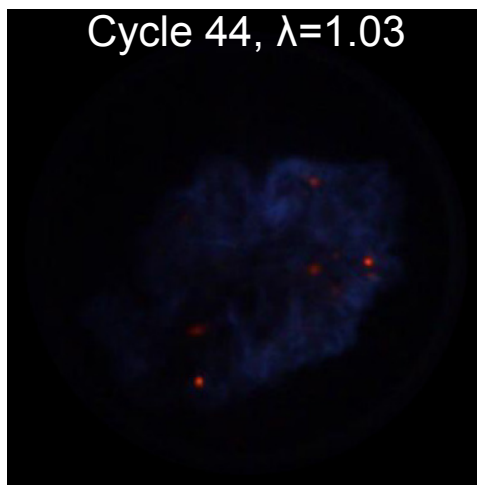**Cycle-by-cycle λ during injection pulse sweep**

- 48 consecutive combustion cycles
- Spark timing: -28 degree ATDC
- Mean IMEP: 3.3 bar
- Head heated to 180 degree F

Warm-up period

selected cases

Stable and rich combustion
with fixed fuel pulse width

Rich-to-lean transition (cycles 26 to 48)
with linearly decreased fuel pulse width

λ (Normalized AFR)

Engine cycle number

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Technical Accomplishments

0.1 CAD (ATDC)
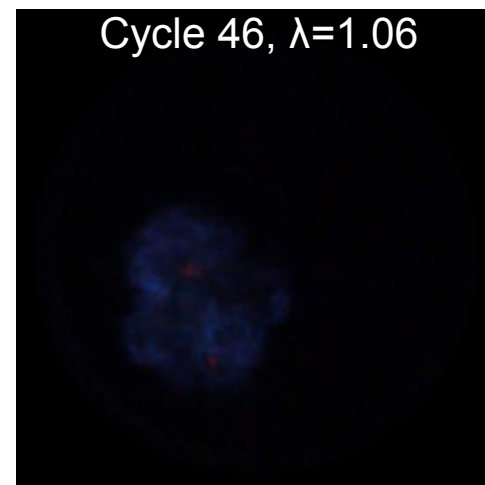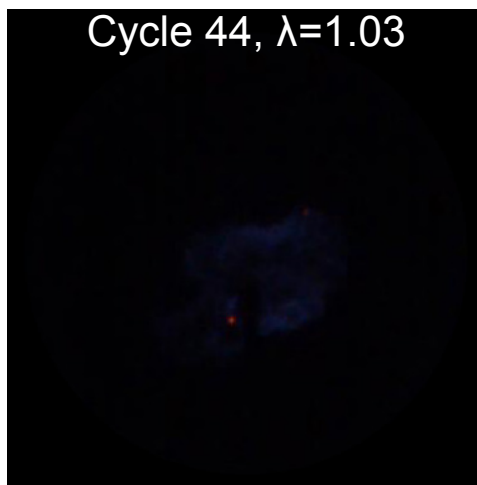
Cycle 27, λ=0.77

Cycle 33, λ=0.85

Cycle 38, λ=0.94

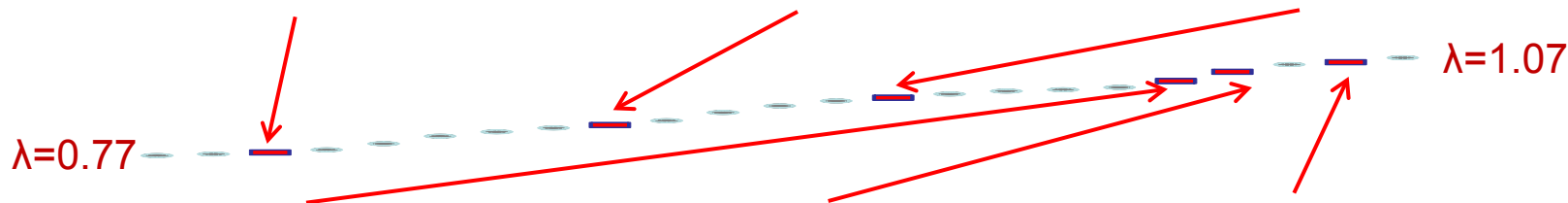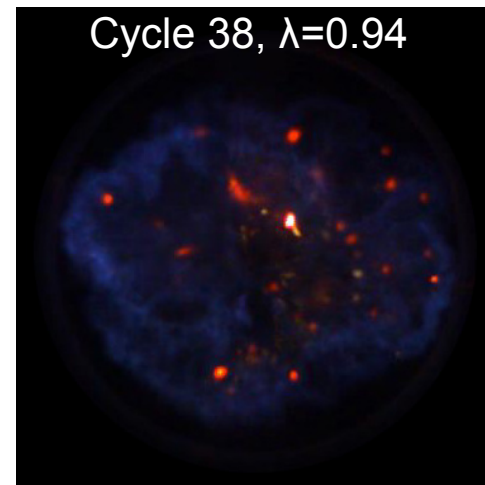Cycle 43, λ=1.00

Cycle 44, λ=1.03

Cycle 46, λ=1.06

λ=0.77

λ=1.07

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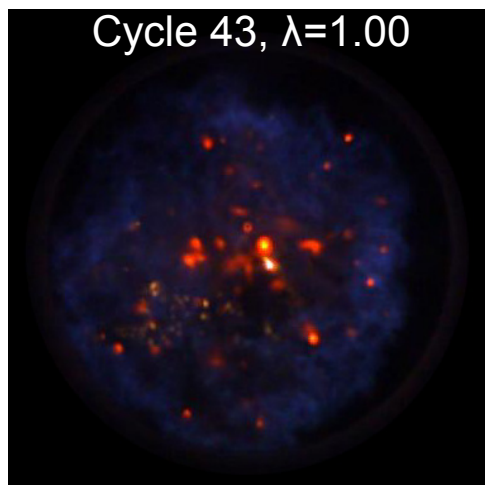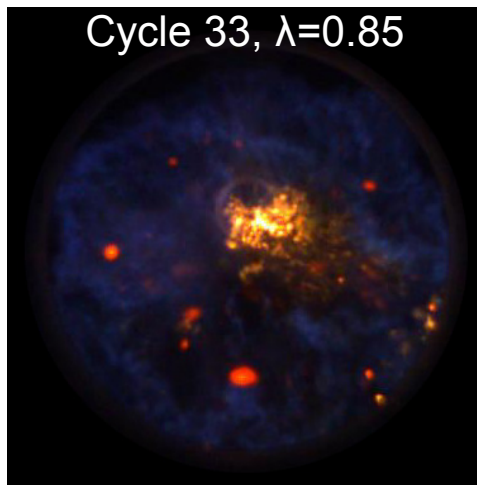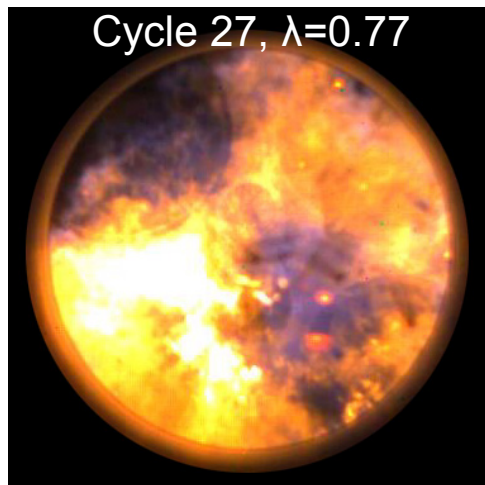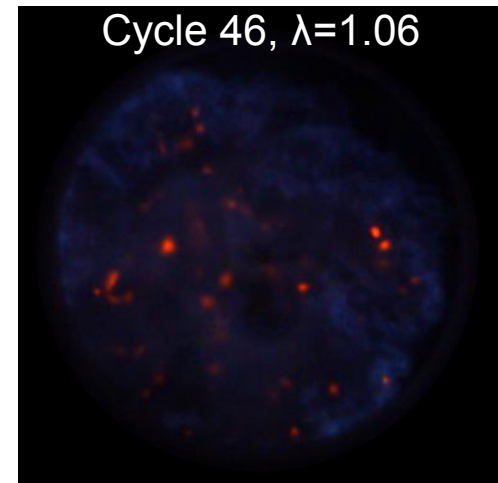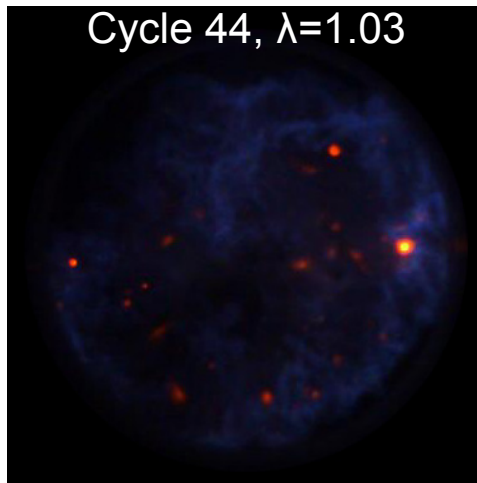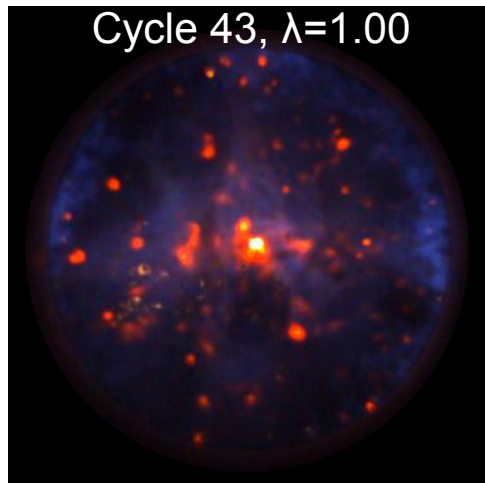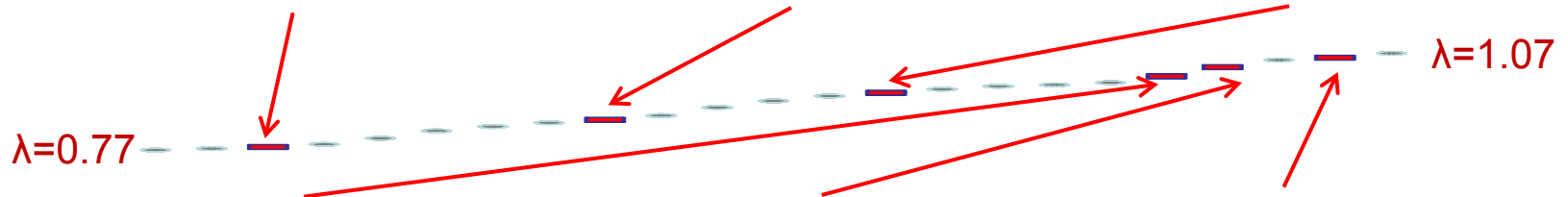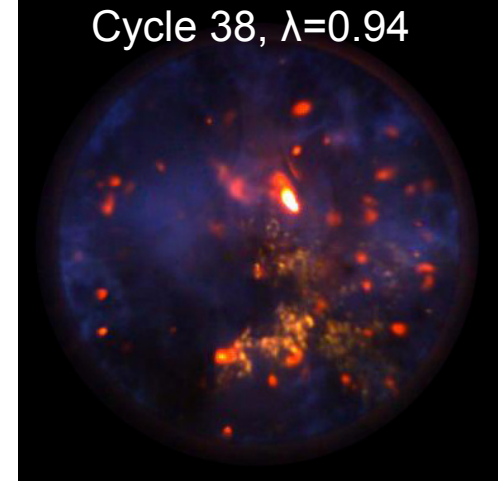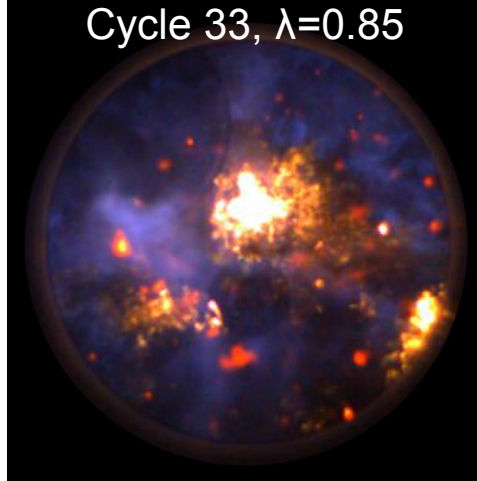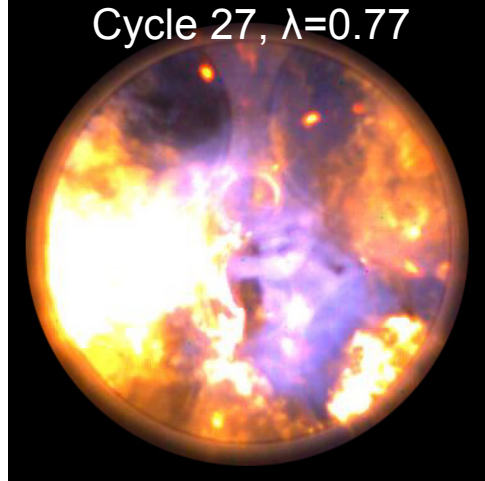
Technical Accomplishments

Technical Accomplishments

Cycle 27, λ=0.77   Cycle 33, λ=0.85   Cycle 38, λ=0.94

Cycle 43, λ=1.00   Cycle 44, λ=1.03   Cycle 46, λ=1.06

17.2 CAD (ATDC)

λ=0.77   λ=1.07

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Technical Accomplishments

HCCI combustion images

-16.3°

-15.4°

2.6°

-6.4°

-14.5°

-13.6°

-12.7°

-10.9°

-9.1°
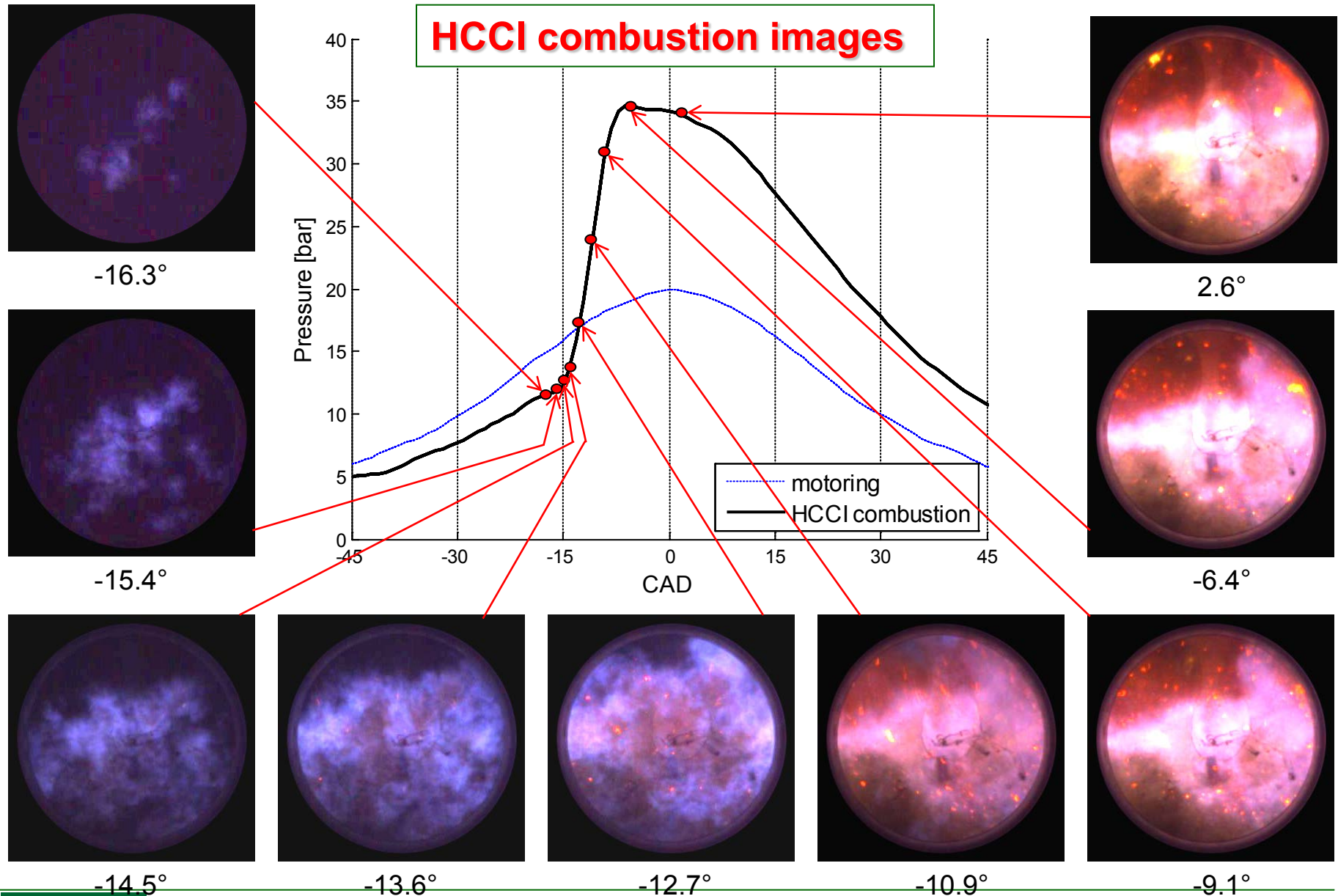
Technical Accomplishments (summary)

❑ Finalized the five-cycle combustion mode transition control strategy and validated it in the HIL simulation environment, where the iterative learning and LQ tracking control are used to control transient fuel and charge air.

❑ Worked with Chrysler/Delphi closely and completed the integration of the two-step valve system on to the Chrysler target head for optical and metal engines

❑ The electrical VVT control strategy was developed on a test bench and also validated on the optical engine setup. Significant engine oil viscosity influences found.

❑ Completed the design of integrating the EVVT system onto both optical and metal engines.

❑ Completed the fabrication of optical engine with two-step valve, EVVT, electrical throttle, intake heat, etc.

❑ Completed the prototype engine control system capable of sampling combustion information every crank degree

❑ Demonstrated SI (transient air-to-fuel ratio) and HCCI combustion in the optical engine

Collaborations

❑ **Support over the past FY**

– Chrysler Group LLC provided design engineering services to integrate the two-step valve and electrical cam phasing systems onto the target engine head (including both optical and metal engines).

– Chrysler Group LLC, Delphi, and MSU integrated the two-step valve onto the target engine head and conducted validation tests at Delphi facility.

– Chrysler Group LLC and Delphi provided engineering design review and support.

❑ **Future support**

– Chrysler Group LLC and Delphi will provide engineering support for modification of the metal HCCI engine.

– Chrysler Group LLC will provide engineering support on final metal engine testing

Collaborations (cont'd)

Technology Transfer

❑ In this year, Chrysler engineers will join both optical and metal engine tests at MSU to further improve the developed control strategy and to make it production viable. This includes:

– The control strategy for combustion mode transition using the hybrid combustion mode with iterative learning and LQ tracking control.

– The HIL (hardware-in-the-loop) simulation technology using the developed control oriented engine model for developing and validating control strategies of HCCI capable SI engines

❑ The MSU team is also working with Ricardo to integrate the developed hybrid combustion model into the Ricardo WAVE-RT modeling tool.

Future Work (During 2012)

❑ Complete the modification of the metal engine (the design is completed and the machining started)

❑ Complete the optical engine tests of model transition control

❑ Complete mapping the metal engine for SI and HCCI combustion (gasoline and E85)

❑ Validate the mode transition control on the metal engine

❑ Final report

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Summary

Relevance: Flex fuel engine technologies for HCCI capable SI engines are being developed to provide smooth mode transition between SI and HCCI combustions

Approach: Using a combination of engine modeling, model-based combustion control and engine experiments to develop a smooth SI and HCCI transition strategy

Key Enablers: Two-step lift, electrical VVT, control oriented engine modeling, hybrid combustion, model-based combustion mode transition, iterative learning

Collaboration: MSU (project lead), Chrysler Group LLC (industrial partner), Delphi (cylinder head) Ricardo (modeling).

Technical Accomplishments:

❑ Finalized the five-cycle combustion mode transition control strategy and validated in the HIL simulation environment, where the iterative learning and LQ tracking control are used to control transient fuel and charge air.

❑ Completed the integration of the two-step valve system on to the Chrysler target head for optical and metal engines

❑ Developed the EVVT control strategy and validated it on the test bench and the optical engine setup; found that the EVVT response time is heavily affected by the engine oil viscosity. The EVVT was integrated onto optical/metal engines.

❑ Completed the fabrication of optical engine with two-step valve, EVVT, electrical throttle, intake heat, etc.

❑ Completed the prototype engine control system capable of sampling combustion information every crank degree

❑ Demonstrated SI (transient air-to-fuel ratio) and HCCI combustion in the optical engine