High Efficiency GDI Engine Research with Emphasis on Ignition Systems

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Overview

Timeline

- Project start: Sept. 2012
- Project end: ongoing
- Percent complete: 10%

Budget

- Funding in FY12: $150k
- Funding in FY13: $90k*
- Funding in FY14: TBD

Partners

- Industrial partners: Ford, Altronic

Barriers

Robust lean-burn and EGR-diluted combustion technology and controls, especially relevant to the growing trend of boosting and down-sizing engines…

- Limited lean and EGR-diluted operating range
- Lack of systematic assessment of ignition systems and their potential in combination with lean/dilute combustion
- Absence of robust modeling tools

*Allocation as of 3/15/2013; $320k total budget anticipated for FY2013

Objectives
Project Relevance

Dilute combustion in advanced gasoline SI engines offers the greatest potential for decreasing oil use, since gasoline is the most widely produced and used fuel in the US — a trend expected to continue for the foreseeable future*

- Maximize efficiency benefits and minimize NOx aftertreatment needs of lean burn GDI engines
  - Broaden the lean and EGR-diluted operating range
  - Investigate ignition systems systematically and determine compatibility with lean/dilute combustion
  - Provide robust modeling tools for rapidly screening proposed designs based on sound metrics

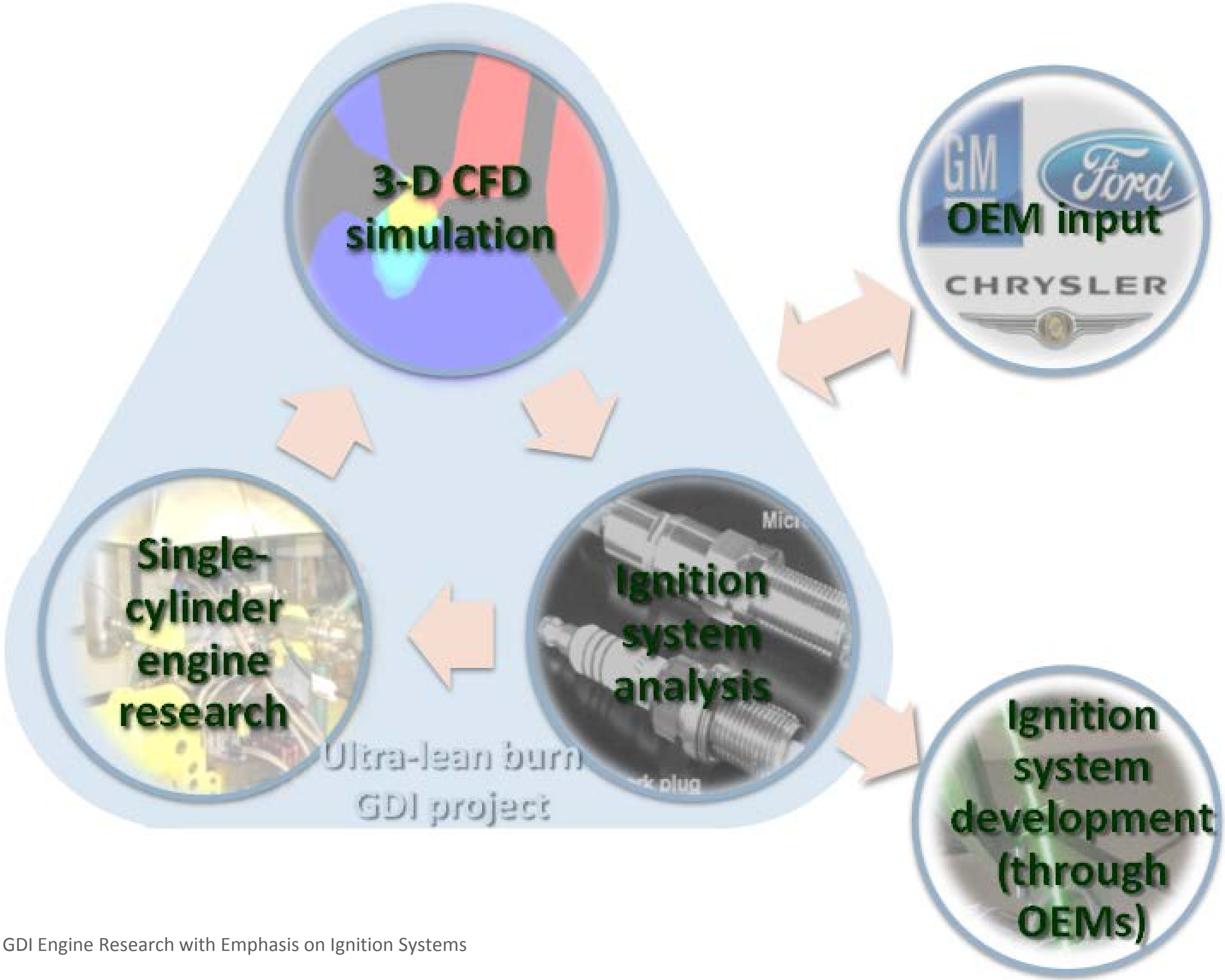
*US DRIVE Advanced Combustion and Emission Control (ACEC) Technical Roadmap for Light-Duty Powertrains

Approach
Technical Aspects

		Efficiency					NOx Emissions	
		Incomplete combustion	Combustion process		Heat transfer	Gas exchange	Catalyst	
			0-10%MFB	10-90%MFB			Before	After
Combustion concept	Lean operation	-	---	---	+	++	++	--
	Stratification	-	+	++	++		--	-
	Charge motion	+	+	++	---	--	-	
Ignition system	Ignition energy		+++	+	-		-	
	Ignition location	+	++	++	+		+	

Interdependencies between ignition system and combustion concept and combined effects on engine efficiency and NOx emissions require integrated assessment

Approach
Organizational Integration

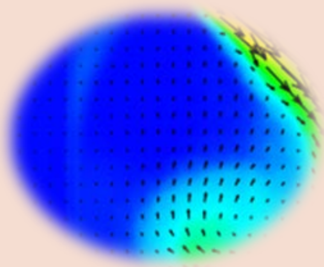


Approach
Milestones

Month/Year	Description	Status
Sept 2012	Project start date	
Dec 2012	Complete single-cylinder engine gasoline setup	Complete
Feb 2013	Complete baseline testing	Complete
Mar 2013	CFD tools validated for lean premixed combustion (baseline)	Complete
April 2013	Upgrade to spray-guided DI configuration	On schedule
May 2013	Complete assessment of advanced coil based system (adjustable spark duration and number)	On schedule
July 2013	Assessment of mixture formation strategies with CFD	On schedule
July 2013	Integration of laser ignition system complete	On schedule
Sept 2013	Complete assessment of laser ignition system	On schedule
Sept 2013	CFD tools validated for advanced ignition	On schedule

Technical accomplishments
Overview

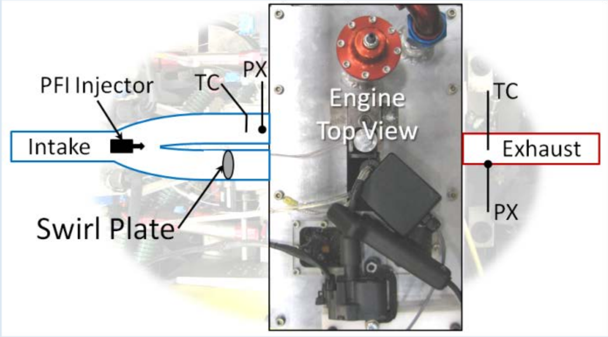
- **Baseline single-cylinder engine**
  - Homogeneous lean combustion
  - Influence of charge motion
  - Ignition system characterization



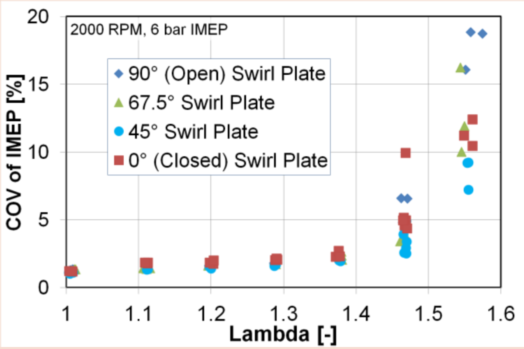
- **Validate CFD for lean homogeneous combustion**
  - Influence of detailed chemistry
  - Analysis of cycle-to-cycle variation
  - Effect of the intake flow on combustion

- **Identify ignition system suppliers**
  - DEIS system (Altronic)
  - Laser ignition system

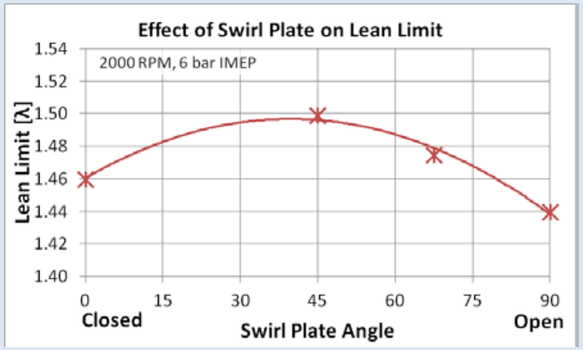
Technical accomplishments
Homogeneous Lean Combustion – Establish Baseline/Limits



- **Experimental Setup**
  - Variable in-cylinder charge motion (swirl plate in right intake runner)
  - Detailed flow characterization from CFD

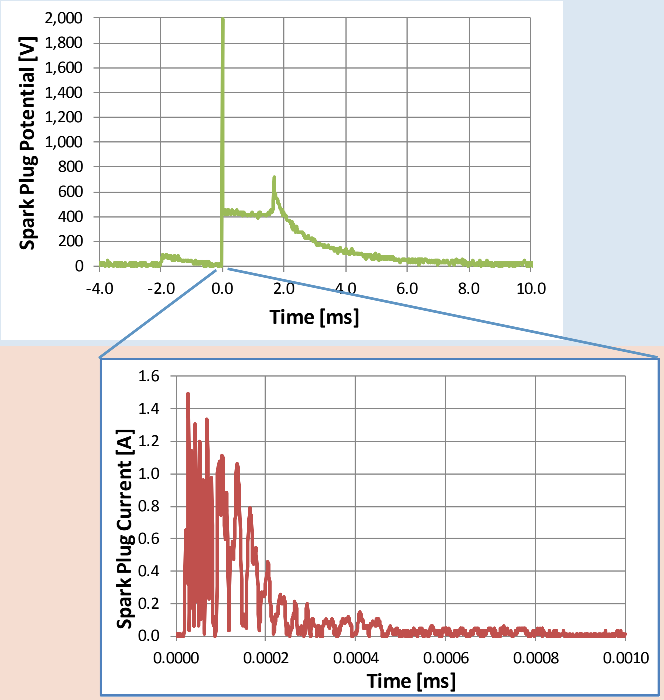


- **Combustion Stability**
  - Similar operation with $\lambda < 1.4$
  - Approaching lean limit $1.4 < \lambda < 1.5$
  - Very poor combustion with $\lambda > 1.5$

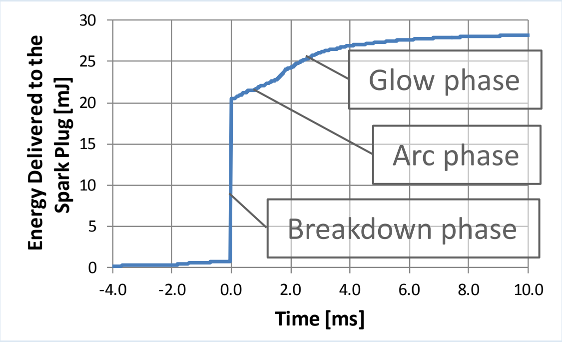


- **Lean Limit**
  - Defined by 5% COV of IMEP which is a typical operating limit for vehicle drivability

Technical accomplishments
Ignition System Characterization

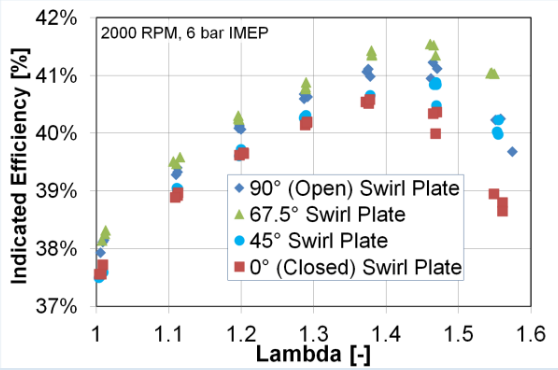


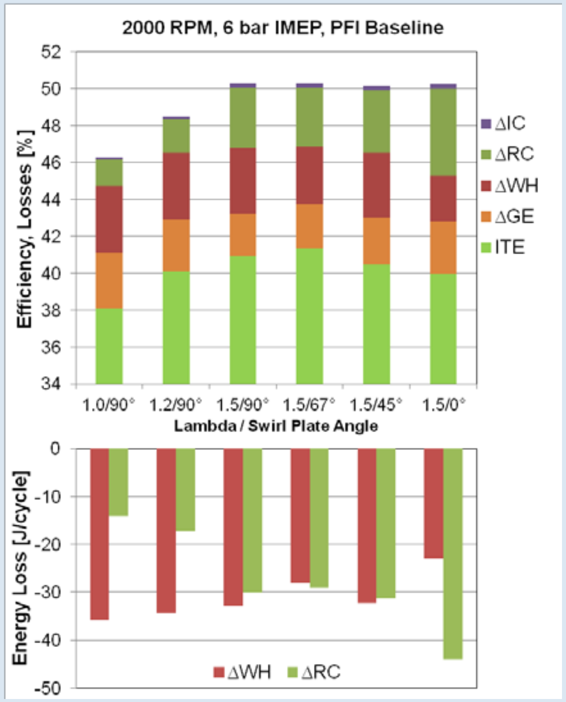
- **High Speed Secondary Coil Voltage**
  - ~1 nanosecond breakdown phase
  - 2 kV for open air operation
  - Up to 40 kV during compression
- **Simultaneous Current Measurement**
  - Enables high fidelity power measurements to quantify ignition energy



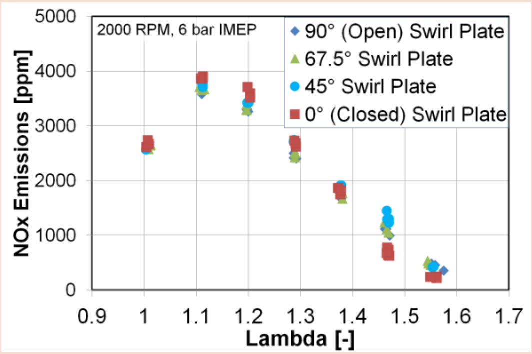
- **Power and Integrated Energy**
  - Peak power during breakdown phase
  - Longer duration arc and glow phases
  - Quantifiable ignition system efficiency

Technical accomplishments
Baseline Efficiency and Emissions

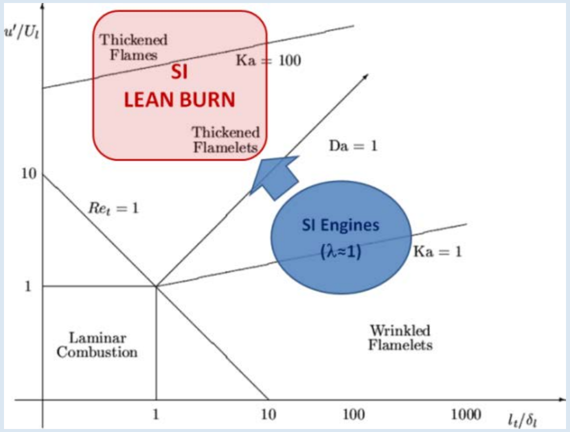




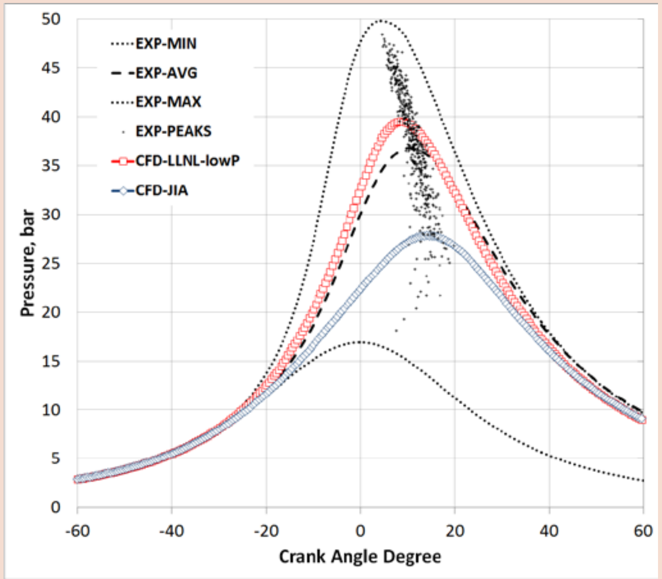
- **Indicated Thermal Efficiency**
  - 4% engine efficiency gain with lean combustion
- **Analysis of Losses**
  - Lean combustion also decreases gas exchange loss (increase again with swirl plate)
  - Complicated tradeoff between real combustion (i.e. phasing and duration) and heat loss to the combustion chamber walls → GDI Concepts!
- **NOx Emissions**
  - Benefit with lean combustion
  - Far above estimated limit of < 5 ppm



Technical accomplishments
CFD: Influence of detailed chemistry



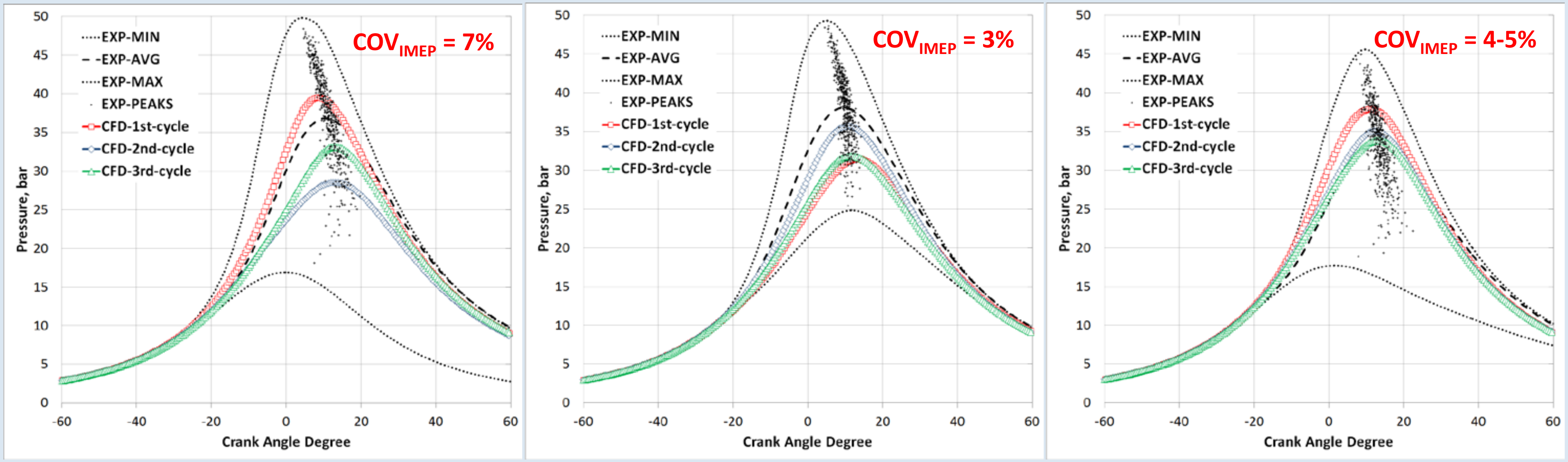
- **Lean Burn Combustion**
  - Laminar flame speed is reduced
  - Flame thickness is increased
  - Chemistry has primary role in determining the flame propagation



- **Detailed Chemistry**
  - Small mechanism (JIA: 38-species, 68-reactions) developed for normal pressure conditions (10-50 bar) delivers poor combustion
  - Larger mechanism (LLNL: 110 species, 488-reactions) optimized for low pressure conditions (2-10 bar) improves the numerical predictions
  - Multi-zone model needs to be used to speed up calculations (1 cycle in 48hrs on 24 CPUs)

Technical accomplishments

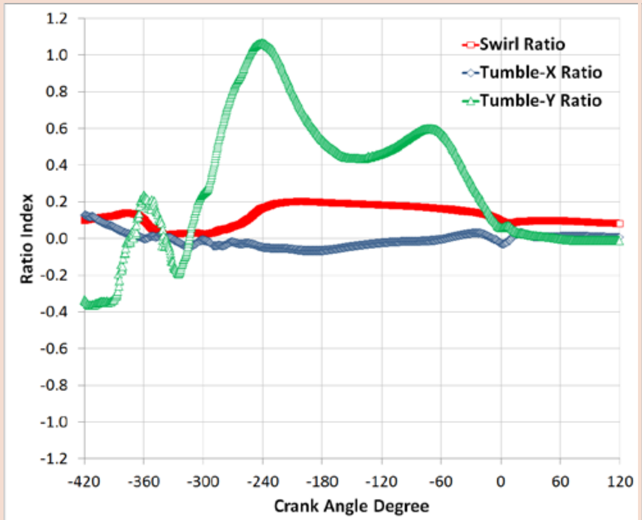
CFD: Experimental and Numerical cyclic variability

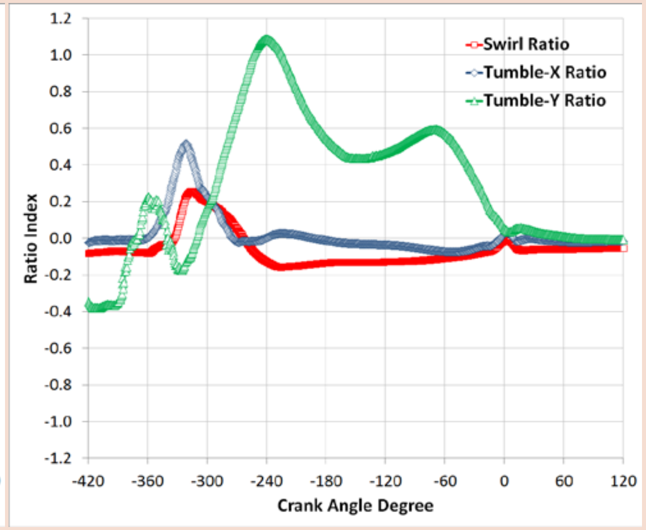


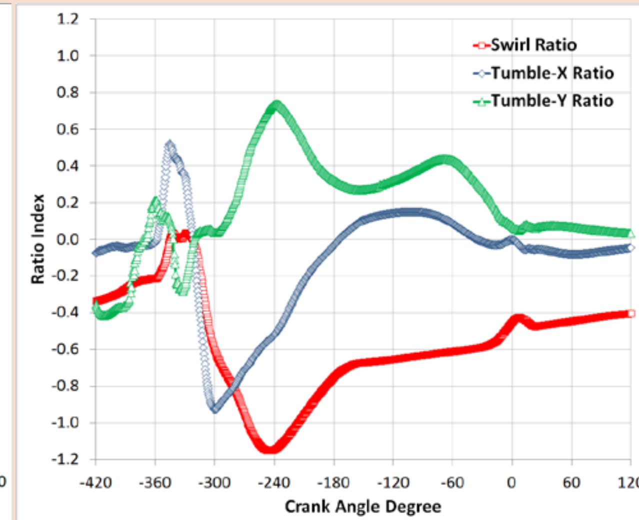
Swirl plate angle = 90° (OPEN) | Swirl plate angle = 45° | Swirl plate angle = 0° (CLOSED)

- **Numerical cycle-to-cycle variation**
  - Featured by the CFD code (CONVERGE) due to Adaptive Mesh Refinement
  - Mesh and turbulence change from cycle to cycle even after removing the effect of initial conditions
  - It’s not a LES. It’s a fine RANS that shows oscillation of pressure close to the AVG experimental trace
  - Conditions that are more unstable in nature show larger oscillation

Technical accomplishments
CFD: Intake Flow Characterization



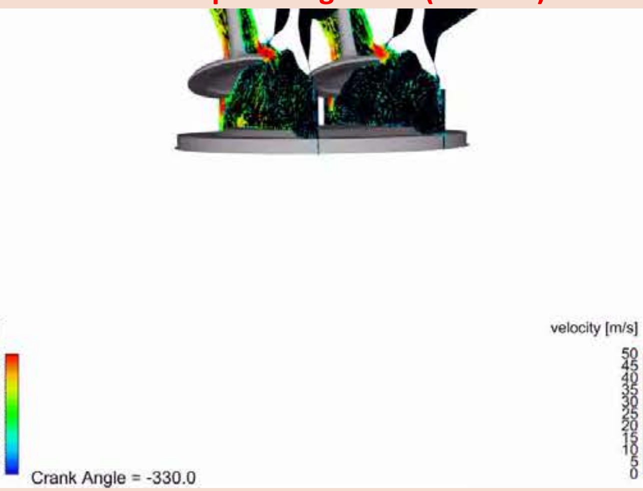




Swirl plate angle = 90° (OPEN)

Swirl plate angle = 45°

Swirl plate angle = 0° (CLOSED)

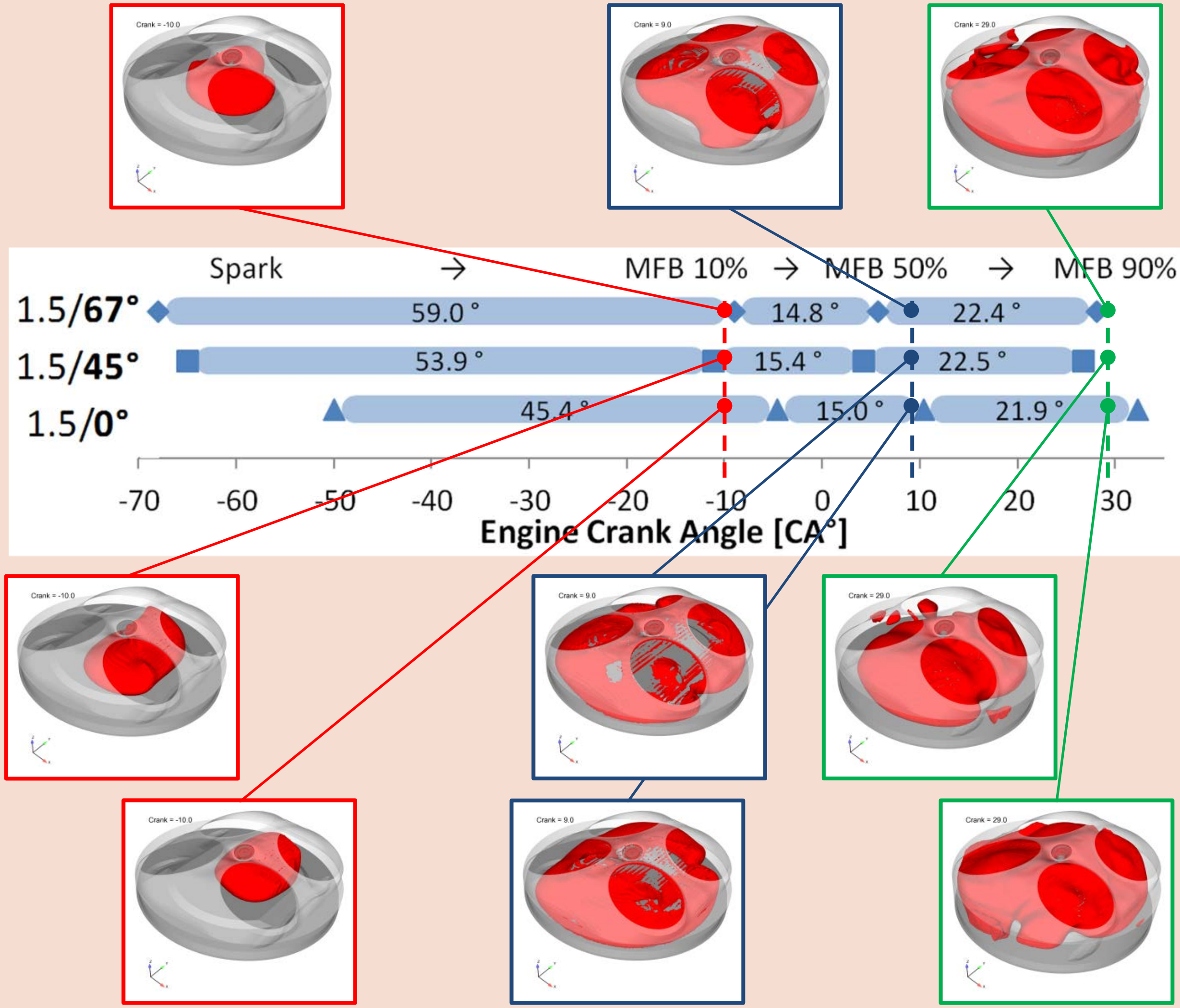


Technical Accomplishments
CFD: Combustion Simulation (1/2)

Swirl plate angle = 90° (OPEN) | **Swirl plate angle = 45°** | **Swirl plate angle = 0° (CLOSED)**

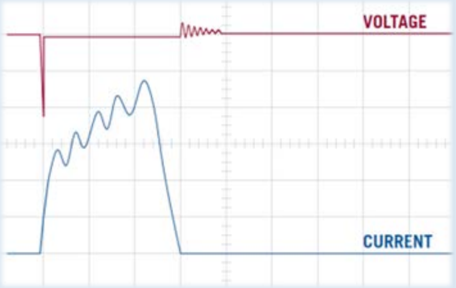
- With the OPEN swirl plate (90°), the flame remains located close to the electrodes (heat losses)
- With increased turbulence (45°), the flame is pushed out from the electrodes resulting in a faster flame kernel development
- With CLOSED swirl plate (0°) turbulence is stronger but dispersed between TUMBLE and SWIRL. Flame propagates faster due to late spark timing (higher temperature) rather than as an effect of the flow-field

Technical Accomplishments
CFD: Combustion Simulation (2/2)



- Baseline intake geometry results in slow flame propagation under lean conditions, leading to high COV and misfire
- Tumble motion, pushing the flame away from the electrodes and towards the high-turbulence region is desirable
- Swirl motion is not beneficial due to high heat transfer losses and quenching at the cylinder walls

Technical Accomplishments
Identifying Ignition Components



- **Directed Energy Ignition System, DEIS**
  - Programmable high-energy coils
  - Variable spark duration and total energy
  - Developed for industrial gas engines

- **Laser Ignition**
  - Lens designed for 14 mm spark plug opening
  - May be focused on a specific point in the combustion chamber

Collaboration and Coordination

- **In-kind Support from Ford Motor Company**
  - Engine hardware
  - Injection equipment
- **Support from Altronic**
  - Supply DEIS ignition system
- **U.S. DRIVE Advanced Combustion & Emissions Control Tech Team**
  - Coordination and update presentations
- **Oakridge National Laboratory**
  - Data exchange for lean burn production versus research results
- **Argonne internal collaboration**
  - Benefit from extensive laser ignition expertise at DERC
  - Simulations are performed on the Fusion Cluster at LCRC

Future work

- **Remainder of FY2013**
  - **Extend experimental activities to spray-guided DI system**
  - **Integrate DEIS system**
    - Evaluate the influence of ignition energy
    - Evaluate the influence of multi-spark operation
  - **Integrate laser ignition system**
  - **Expand multi-cycle simulations**
    - Validate cycle-to-cycle variability predictions against experimental results
  - **Simulate advanced ignition systems**
    - Realistic multi-spark simulations
    - Basic laser ignition simulations
- **FY2014**
  - **Evaluate plasma, microwave and pre-chamber ignition systems**
  - **Upgrade simulation code with representative ignition sub-models**

Summary

- **Project focused on integrated assessment of dilute gasoline combustion with advanced ignition systems**
- **Combined experimental and simulation-based assessment**
  - Baseline experimental data established on single-cylinder engine
  - Detailed characterization of ignition event
  - Loss analysis applied to quantify efficiency potential
  - 3D-CFD simulation validated against experimental results
  - Impact of charge motion quantified with experimental and simulation results
  - Simulation approach allows for quantitative assessment of cyclic variability
- **Next steps**
  - Experimental assessment of DEIS system and laser ignition
  - Multi-cycle simulations and integration of ignition sub-models