Low-Temperature Gasoline Combustion (LTGC) Engine Research

– Previously known as HCCI / SCCI –

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June 8, 2016 – 9:00 a.m.

U.S. DOE, Office of Vehicle Technologies
Annual Merit Review and Peer Evaluation

Program Managers: Gurpreet Singh & Leo Breton **Project ID: ACE004**

Overview

Timeline

- Project provides fundamental research to support DOE/Industry advanced engine projects.
- Project directions and continuation are evaluated annually.

Barriers

- Rapid control of LTGC / HCCI combustion timing
- Spark-Assisted LTGC / HCCI
- Improved stability / robustness of LTGC combustion
- Advanced fuel-injection strategies
- Improved understanding of LTGC fundamentals

Budget

- Project funded by DOE/VT:
  FY15 – $680k
  FY16 – $600k

Partners / Collaborators

- Project Lead: Sandia ⇒ John E. Dec
- Part of Advanced Engine Combustion working group – 15 industrial partners
- General Motors – in-depth collaboration
- Cummins – spark-plug cylinder heads
- LLNL – support kinetic modeling
- Co-Optima Fuels project
- Chevron – advanced fuels for LTGC
- Sandia LDRD – fuel injection

Objectives - Relevance

Project objective: to provide the fundamental understanding (science-base) required to overcome the technical barriers to the development of practical LTGC / HCCI engines by industry.

FY16 Objectives ⇒ address barriers, particularly Controls and Robustness

- Performance mapping with new low-swirl, spark-plug capable cylinder head: Compare thermal efficiency (TE) & load range with data from old head.
- Evaluate performance with RD5-87 (typical regular 87 AKI, E10 gasoline) compared to Tier-2 certification gasoline (CF-E0) for premixed (PM) fueling and with partial fuel stratification (PFS).
- CA50 control and improved robustness using Double-DI PFS (DDI-PFS) ⇒ Determine the potential for CA50 control and improved EGR tolerance.
- Initial studies of Spark Assist (SA): Determine CA50 control and intake-temperature (T_{in}) tolerance at selected conditions.
- Support Modeling: Chemical-kinetics at LLNL and related RCM experiments at ANL, and CFD modeling at GM.

Response to Reviewer Comments

- **Reviewers made many positive comments.** ⇒ **We thank the reviewers**
- **Several comments indicated ⇒ focus less on high efficiency and high loads and more on ways control combustion timing and operation at lower boost.**
  - ► **We have accelerated plans to shift research in these directions, as reflected in the FY16 objectives (prev. slide) and explained in greater detail below.**

Specific comments

1. **Accelerate installation of spark-plug head and studies of spark assist (SA)**
   - ► **Several mechanical/technical problems were encountered that delayed installation of head.**
   - ► **Head was installed latter part of FY15, debugged. Initial studies of SA have been conducted.**
2. **Studies of DDI-PFS should include CA50 control methodologies.**
   - ► **DDI-PFS has strong potential for rapid CA50 control and for increased robustness.**
     ⇒ We have shifted the focus of DDI-PFS studies to these objectives.
3. **Concerns that high boost can be difficult with LTGC**
   - ► **PFS requires that fuel autoignition be ϕ-sensitive ⇒ typically greater at higher boost.**
   - ► **Investigated ϕ-sensitivity over a wide range of boost for CF-E0 and RD5-87**
     ⇒ Found good potential that PFS can provide benefits down to P_{in}=1.3 bar, better for RD5-87
   - ► **New studies have been conducted at lower boost ⇒ additional low-boost studies planned.**
4. **Need to show Combustion Noise Levels (CNL) as well as Ringing Intensity (RI)**
   - ► **CNL values are presented and discussed.**

Approach

Overall Approach: Use a combination of metal- and optical-engine experiments, analysis & modeling to build a comprehensive understanding of LTGC processes.

- **Metal Engine**
  - ► Modify new cylinder heads to install spark-plug (SP) ports.
    - > Work with Cummins on design, SP port installation, & new pressure transducer (PT) port
    - > In-house modifications to SP-head for Bosch HDEV 5.1 GDI injector (300 bar capable).
  - ► Well-controlled experiments to **1)** evaluate SP-head performance, and investigate:
    2) DDI-PFS: develop methods of varying fuel stratification to obtain injection-timing control of CA50, increased CA50 tolerance, and improved stability.
    3) Spark-Assist: systematically adjust spark time for CA50 ctrl. & T_{in} compensation.
- **Optical Engine** – adaptation of SP-head and installation will follow.
- **Fuels** – Worked with GM to specify a research-grade E10 regular gasoline, RD5-87, and compare performance with CF-E0. (Prior to recent E10 Tier 3 cert. gas.)
- **Analytical Techniques** – Apply our recently developed techniques to understand: **1)** changes in energy-loss distribution, and **2)** noise levels, CNL
- **Computational Modeling**: **1)** Collaborate with LLNL on kinetic mechanism for RD5-87, and **2)** with GM on CFD modeling for improved understanding of PFS.
- Combining techniques provides a better understanding and more-optimal solutions.
- **Transfer results to industry:** 1) physical understanding, 2) improved models

Approach – Milestones

- ✓ **September 2015**
  Complete installation and initial testing of new low-swirl cylinder head with spark-assist capability.

- ✓ **December 2015**
  Map performance of SP-head **(Head #2)** over a range of operating conditions and compare with previous head **(Head #1)**.

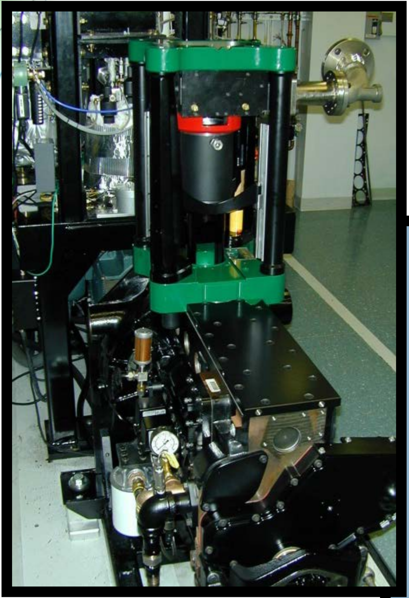
- ✓ **March 2015**
  Complete installation of spark ignition system and initial study of spark-assisted (SA) LTGC.

- ✓ **June 2016**
  Present an overview of project accomplishments and directions at the DOE Annual Merit Review.

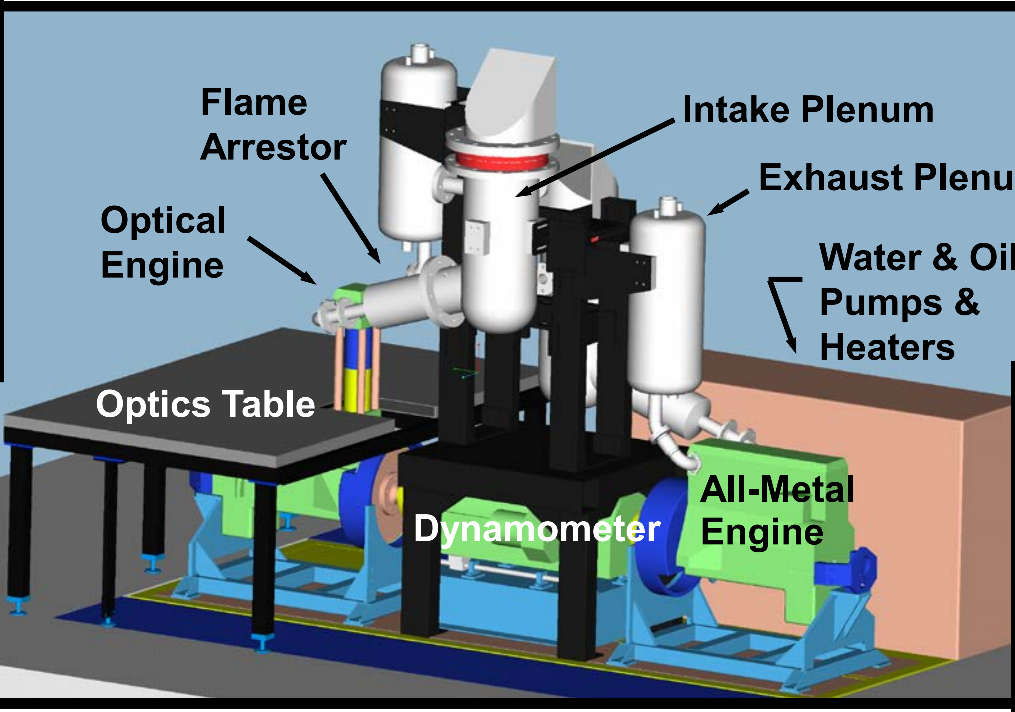
- **September 2016**
  Map the operating range for effective DI-PFS with E10 regular gasoline at a compression ratio of 14:1 (plan to switch soon from current CR = 16:1 to 14:1).

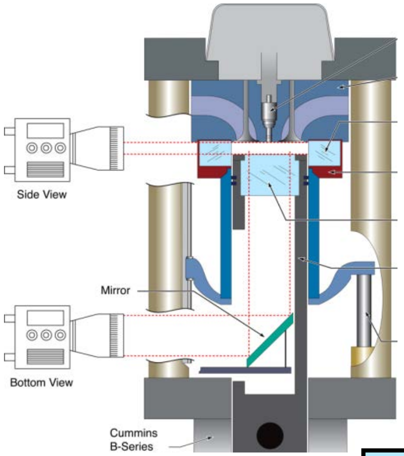
Sandia LTGC Engine Laboratory

- Matching all-metal & optical LTGC research engines.
  - Single-cylinder conversion from Cummins B-series diesel.



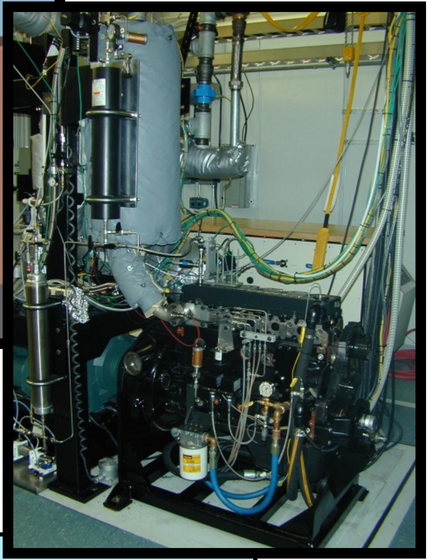
Optical Engine





- Bore x Stroke = 102 x 120 mm
- 0.98 liters, **CR = 16:1**, switch to 14:1

All-Metal Engine



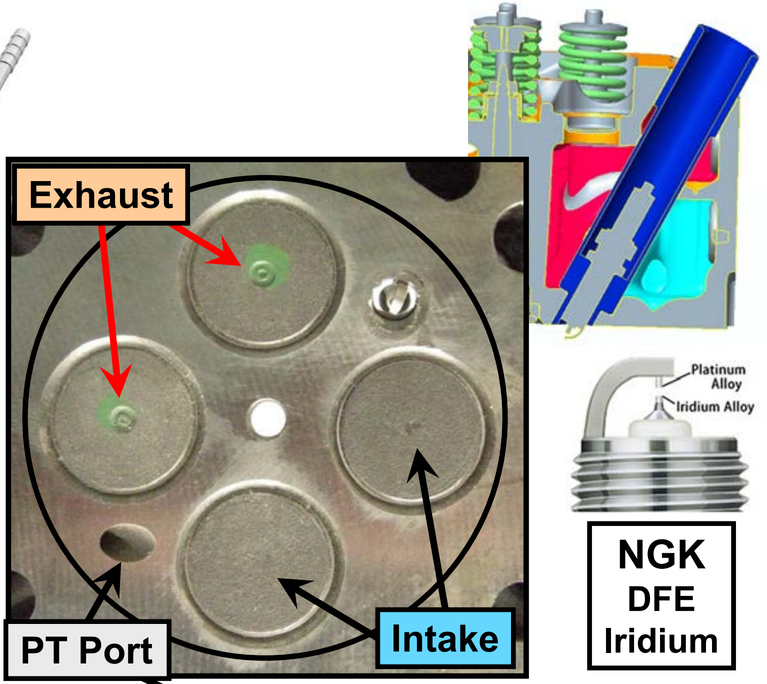
Unless noted: Ringing ≤ 5 MW/m^2 & spd = 1200 rpm
NO$_x$ & soot emiss. more than 10x below US-2010

Overview of Accomplishments

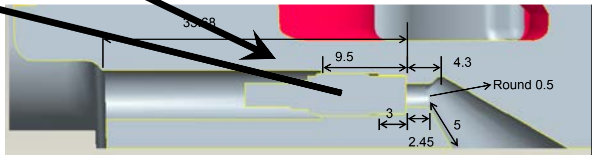
- Completed installation and shakedown testing of new spark-plug capable, low-swirl cylinder head (Head #2).
- Conducted performance mapping of Head #2 and comparisons with Head #1 for both premixed & Early-DI fueling ⇒ TE, high-load limits, CNL, etc.
  - Applied energy-loss analysis tools (developed in FY15) to understand differences.
- Evaluated performance of a research-grade regular 87-AKI, E10 gasoline (RD5-87) and compared to high-octane, E0 certification gasoline (CF-E0).
- Demonstrated CA50 control over a wide range by varying injection timing for a DDI-PFS fueling method:
  - Retard late-DI timing ⇨ incr. strat. ⇨ adv. CA50
- Showed that DDI-PFS can also substantially increase robustness (EGR & CA50 tolerance) and increase stability for an extended load range.
- Demonstrated Spark-Assisted (SA) LTGC for CA50 control and increased tolerance to variation in T_{in} (compensate for T_{in} variation).
- Collaborated with LLNL on development of a kinetic mechanism for RD5-87 and related RCM measurements at ANL, and with GM on CFD modeling.

Low-Swirl Spark-Plug Head ⇒ *“Head #2”*

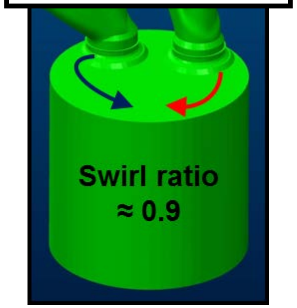
- Worked with Cummins to design SP capability and fabricate.
  - SP port in location of original D = 10 mm PT (AVL QC34C)
- Install new PT port through fire-deck
  - Very small, D = 5 mm (AVL GH15D)
  - For CI studies, 2nd GH15D in SP port.
- Problems w/ small PT, not all are durable.
- Both heads are low-swirl, but:
  - <u>Head #1</u>, custom anti-swirl plate directs helical port flow against tangential port to create a **counter-swirling flow**.
  - <u>Head #2</u>, ports designed to give low swirl ⇒ thought to produce tumble flow.
- Central-mount Bosch HDEV 5.1 GDI injector ⇒ 300 bar capable.
- Same valves / camshaft / rocker assembly for both heads.



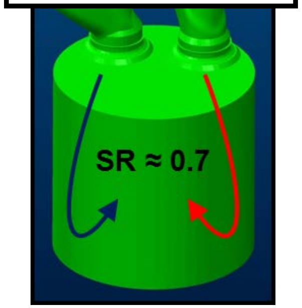
NGK DFE Iridium



Head #1
Counter-swirling streams



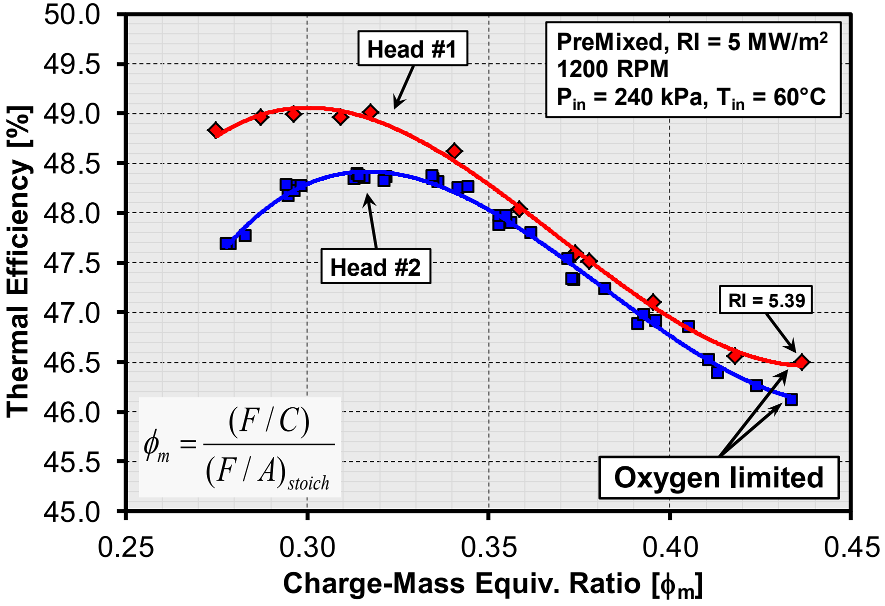
Head #2
Assumed tumble air motion



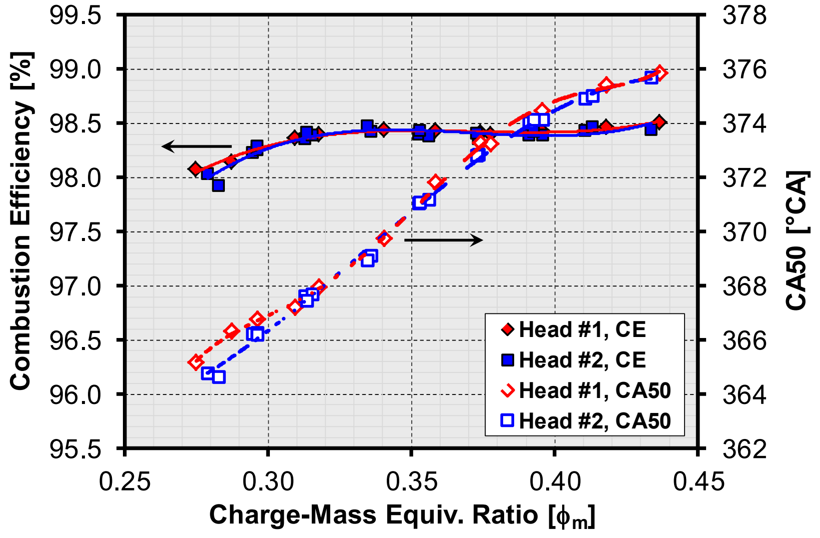
Thermal Eff. (PM) – Spark-Plug Head #2

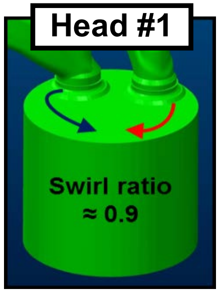
- Initial testing of Head #2 used:
  - CF-E0 ⇒ large database for Head #1
  - Premixed (PM) fueling to eliminate differences due to fuel inject & mixing.
- $\phi_m \geq$ **0.34:** TE with Head #2 is just slightly lower (~0.2 %-units).
- $\phi_m <$ **0.34:** greater TE loss w/ Head #2
- Cause is not well understood:
  - Combst. Eff (CE) and CA50 are similar
  - EGR requirement & γ also similar
- Analysis shows increased HT with Head #2 is the most likely explanation.
  - Possibly high-tumble flow breaks down near TDC and increases HT.
  - Greater at low ϕ_m since CA50 is closer to TDC.
- Is counter-swirl better for low HT?

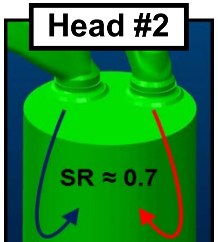
PreMixed, CF-E0, P_{in} = 2.4 bar, RI = 5 MW/m²



$$\phi_m = \frac{(F/C)}{(F/A)_{stoich}}$$



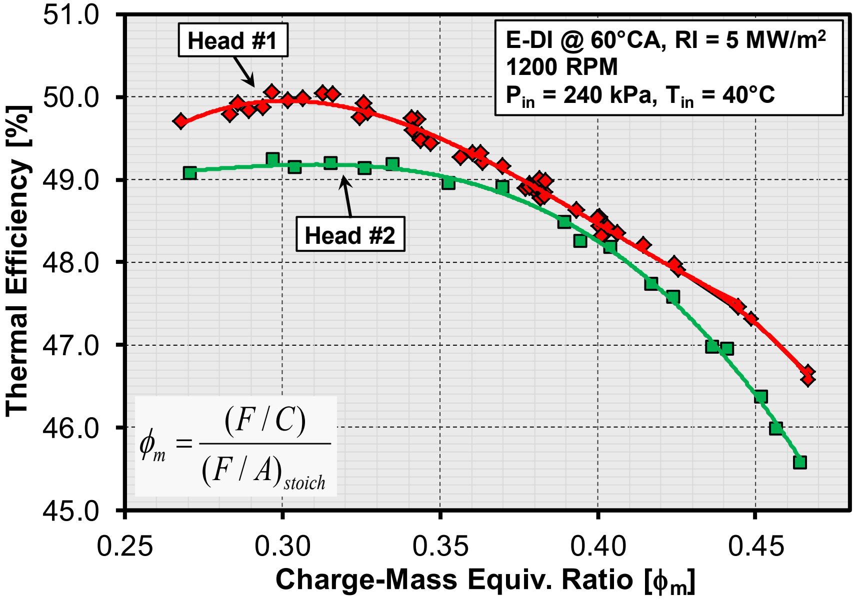


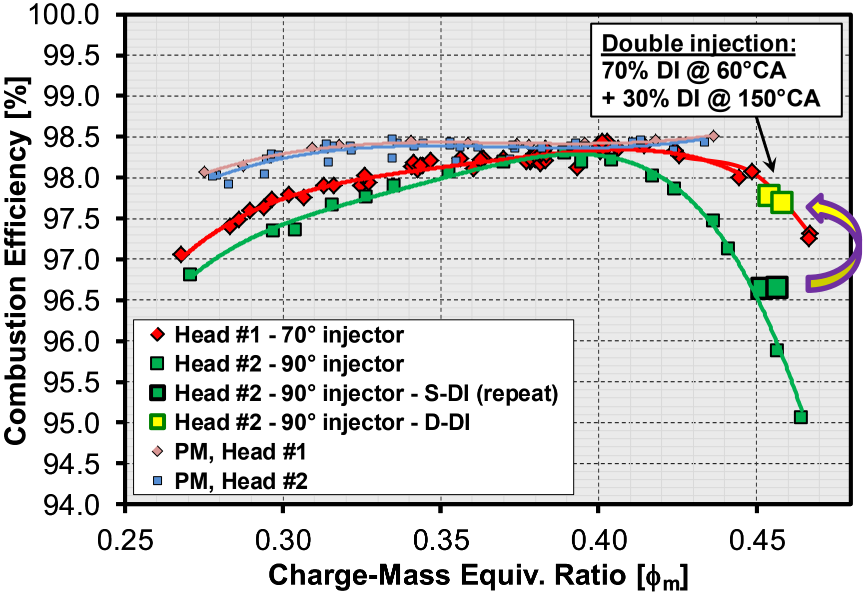


Thermal Eff. (Early-DI) – Spark-Plug Head #2

- Compare heads, Early-DI @ 60° CA
  - T_{in} = 40°C vs. 60°C for Premixed
  - Injection Press = 120 bar, both heads
- Overall TE higher than PM mainly due to lower $T_{charge} \Rightarrow$ higher γ & lower HT.
- **$\phi_m \leq 0.4$:** Trends similar to PM, but
  - For $\phi_m \leq 0.35$: TE reduction with Head #2 slightly larger for E-DI due to lower CE with Head #2 $\Rightarrow$ higher CO.
- **$\phi_m > 0.4$:** TE of Head #2 falls below Head #1, rapid drop in CE $\Rightarrow$ higher CO
- Increased CO at low and high ϕ_m indicate a less well-mixed charge with Head #2.
  - Low ϕ_m overly lean zones make CO
  - High ϕ_m rich zones make CO – high EGR
- Counter-swirl improves mixing for Early-DI fueling with Head #1.

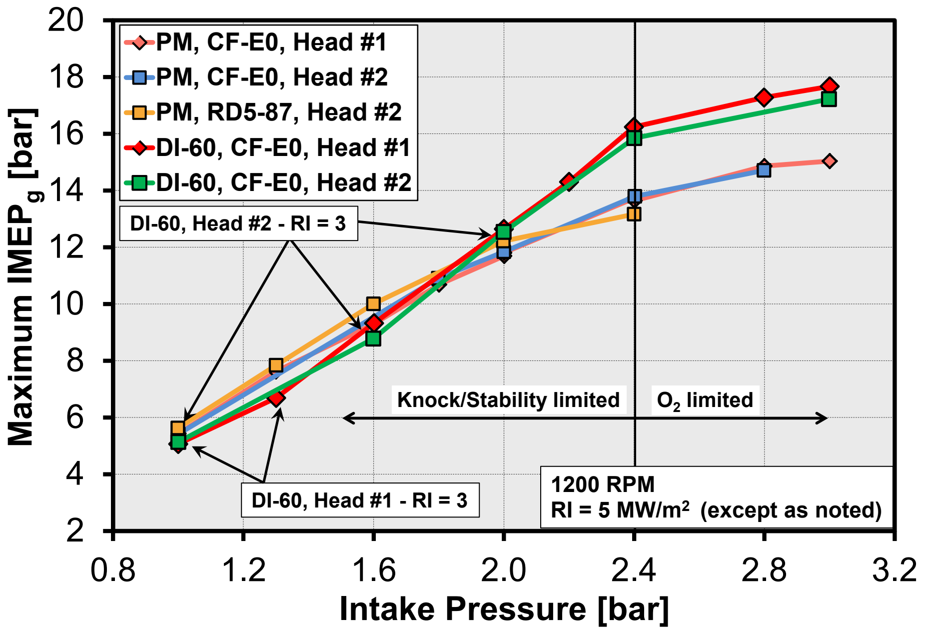
Early-DI, CF-E0, P_{in} = 2.4 bar, RI = 5 MW/m^2

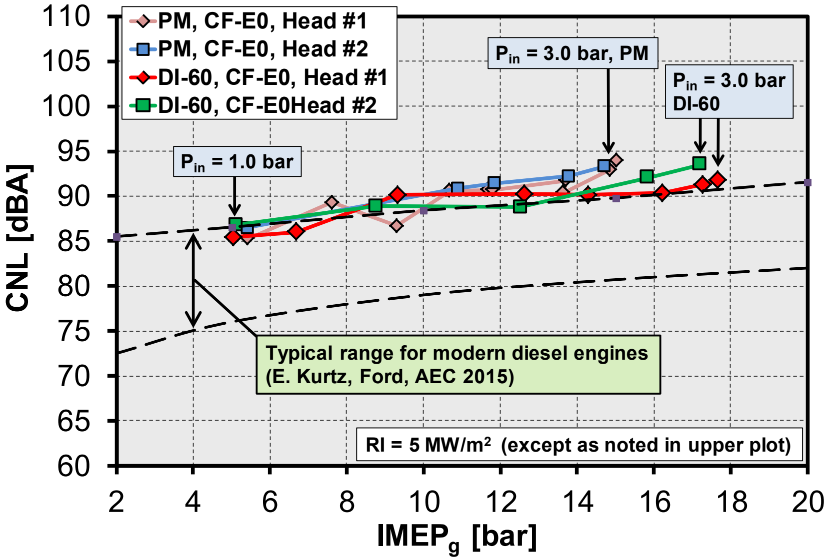




High Load Limit as a Function of Boost

- Max. load for PM fueling with CF-E0 nearly identical for two heads, all P_{in}.
  - Oxygen limited P_{in} > 2.4 bar (CF-E0).
- RD5-87, PM is similar to CF-E0.
  - Max. load slightly greater, $P_{in} \leq 2.0$ bar.
    ⇒ Higher ϕ_m for RI = 5 MW/m^2.
  - Max. load is less at P_{in}=2.4 bar
    ⇒ More reactive, requires more EGR, becomes O$_2$-limited at P_{in} < 2.4 bar.
- Early-DI fueling: Max. load quite similar for two heads, all P_{in}.
  - Highest load at P_{in} = 3.0 bar
    ⇒ 17.2 bar IMEP$_g$ for Head #2 vs.
    ⇒ 17.7 bar IMEP$_g$ for Head #1
- Combustion Noise (CNL) is similar for all max. load curves, for RI = 5MW/m^2
  - Close to high end of diesel CNL range.
  - Could reduce CNL by small CA50 retard
    5 dBA reduction for 0.8 %-units less TE

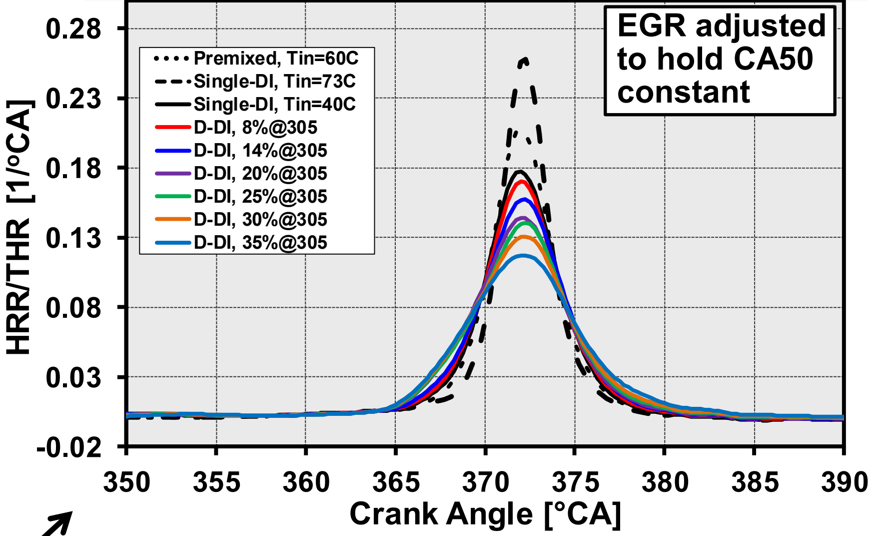


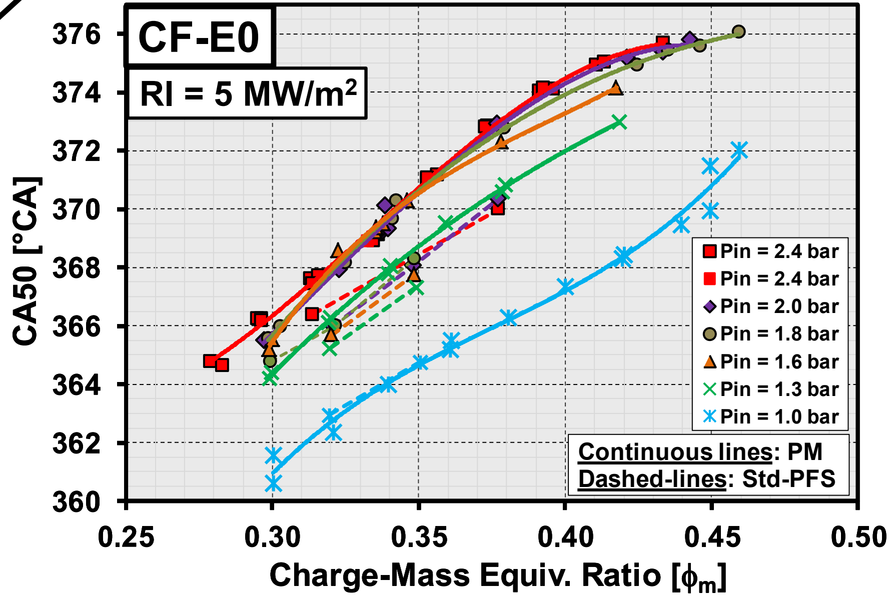


Injection-Timing/PFS to Control LTGC

- If the fuel's autoignition timing varies with the local in-cyl. ϕ_m, said to be **ϕ-sensitive** ⇒ richer regions autoignite faster.
- Partial fuel stratification (PFS) can be used to provide several benefits.
  - Reduced HRR for higher loads & higher TE. ⇒ Shown in previous years.
  - Combustion-timing control
  - Increased robustness, i.e. tolerance to variation in EGR and CA50
- **Std-PFS** = most Premixed + late DI
  Double-DI PFS = most Early-DI + late DI
  ⇒ late-DI timing & fraction adjusts strat.
- For what P_{in} range are fuels ϕ-sensitive? ⇒ Direct measurement very tedious.
- Use CA50 adv. for RI = 5 MW/m² with std-PFS vs. PM as a measure of ϕ-sensitivity.
  - Here **std-PFS = 90% PM + 10% at 310° CA**.

T_{in} = 40°C, P_{in} = 2.4 bar, ϕ_m = 0.4, 1200 rpm





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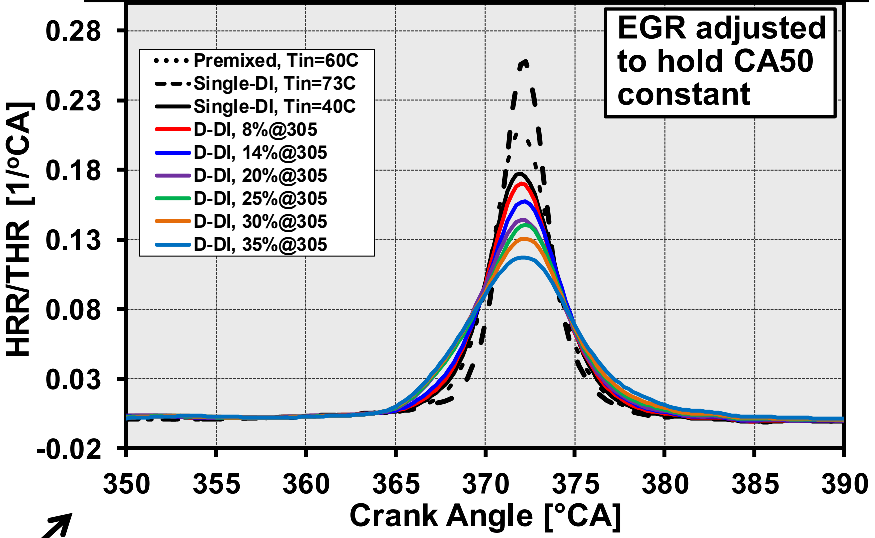
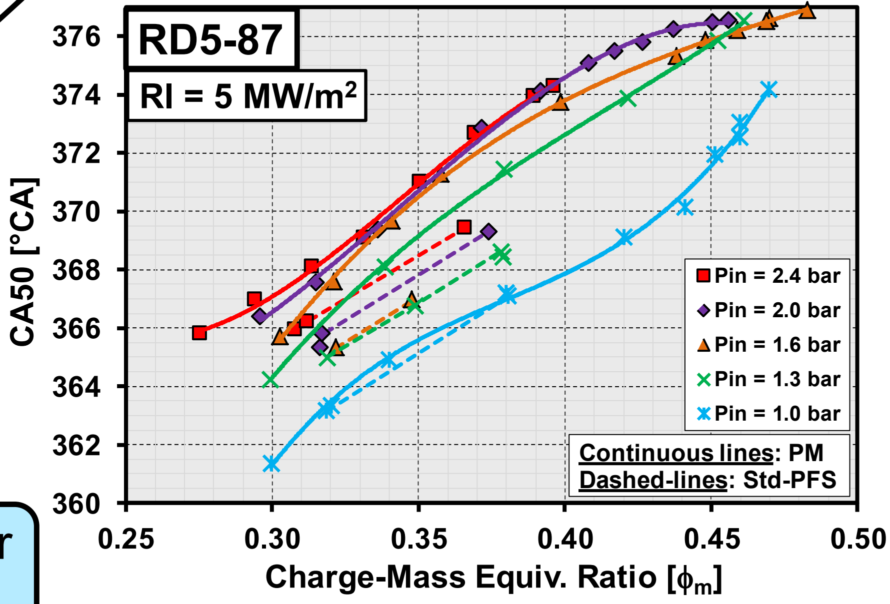
  - Here **std-PFS = 90% PM + 10% at 310° CA**.
- Both fuels ϕ-sensitive from P_{in} = 2.4–1.3 bar ⇒ RD5-87 more ϕ-sensitive, all ϕ_m s & P_{in}s.

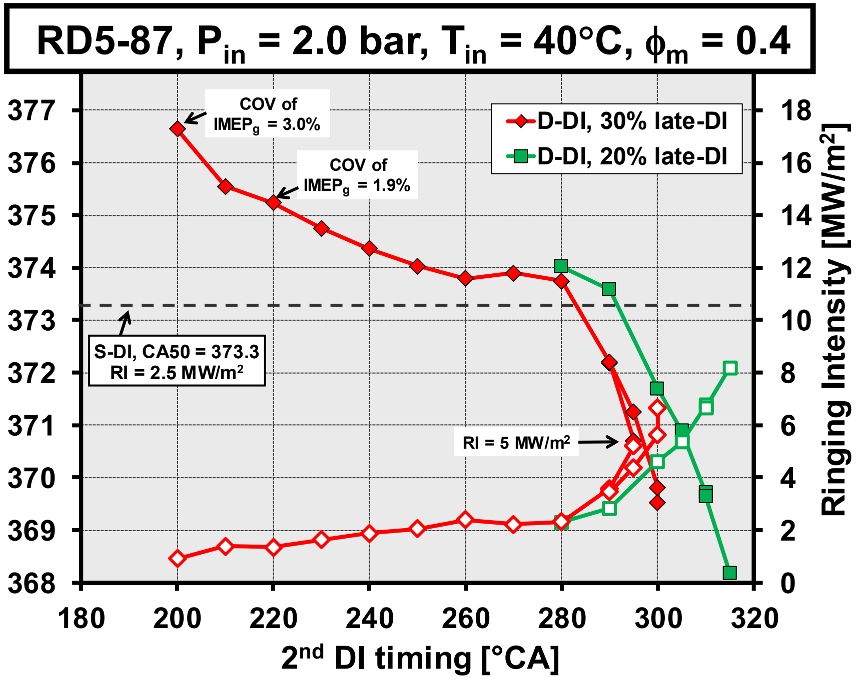
T_{in} = 40°C, P_{in} = 2.4 bar, ϕ_m = 0.4, 1200 rpm



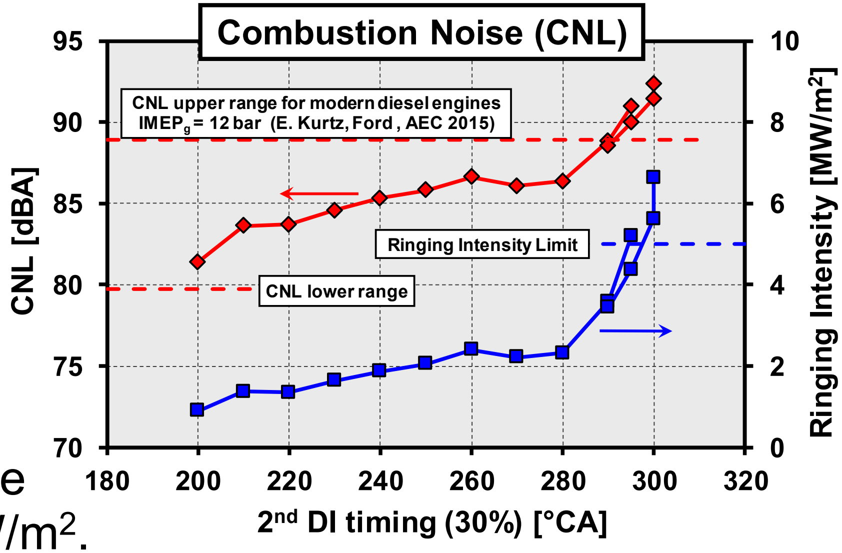


CA50 Control with Injection-Timing

- Apply Double-DI (DDI) PFS to control CA50.
- Procedure:
  1. Set initial conditions ⇒ adjust CA50 to give RI=2.5 MW/m^2 for single, Early-DI injection.
  2. Switch to DDI with 70% Early-DI at 60°CA & 30% late-DI with variable timing (70/30%).
  3. Hold EGR and T_{in} constant while sweeping late-DI timing.
- Late-DIs from 200 – 280° CA retards CA50 compared to Single-DI at 60°CA (S-DI-60).
  - Indicates better mixing than S-DI, which already gives some PFS. ⇒ RI < 2.5 MW/m^2
- Late-DIs from 280 – 300° CA advance CA50 significantly due to greater stratification. ⇒ RI = 2.3 – 6.1 MW/m^2
- **CA50 was adjusted 6.7° CA** with 70/30% (4.5° COV-IMEP$_g$ = 1.9% to RI = 5 MW/m^2)
- With DDI-80/20%, **CA50 ctrl. range 8.6° CA**
- CNL trend is similar to RI ⇒ below upper range for diesels for most of the sweep, RI ≤ 3.5 MW/m^2.



RD5-87, P_{in} = 2.0 bar, T_{in} = 40°C, ϕ_m = 0.4

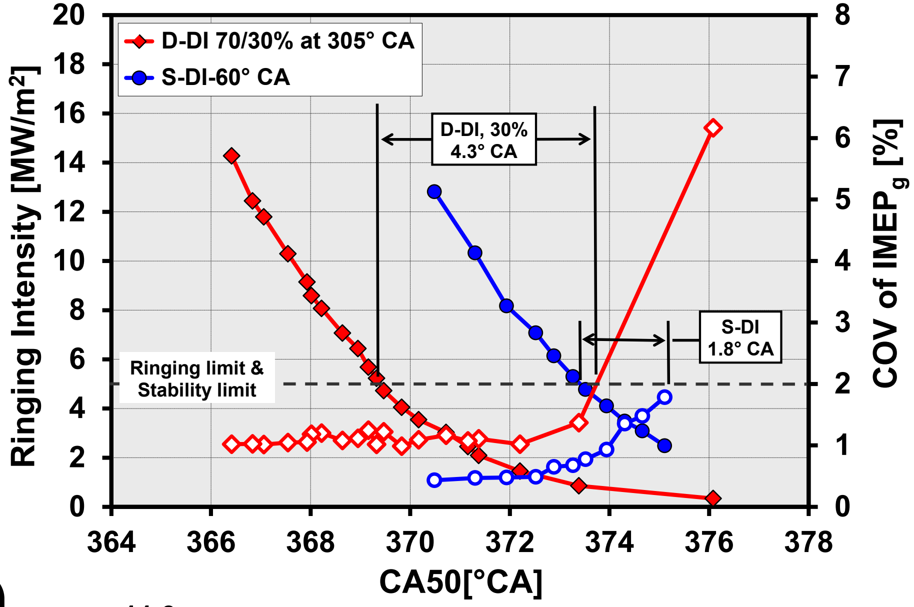


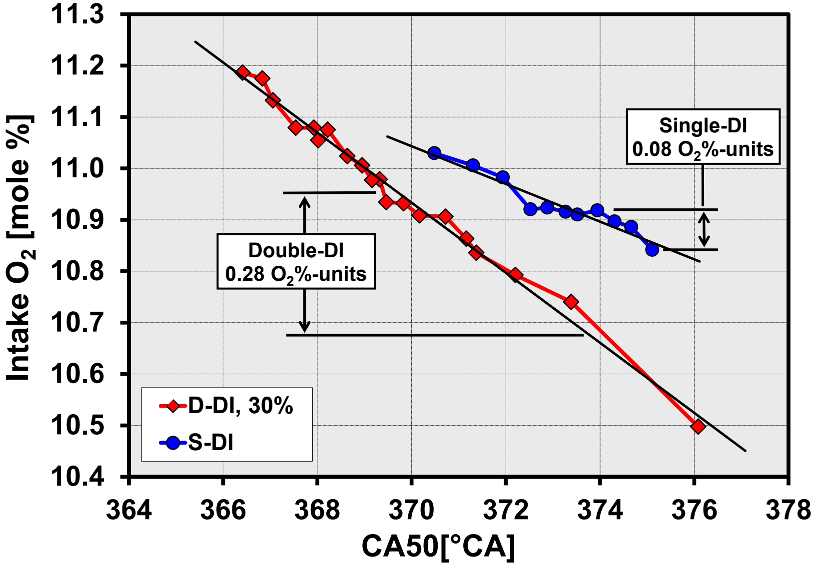
Combustion Noise (CNL)

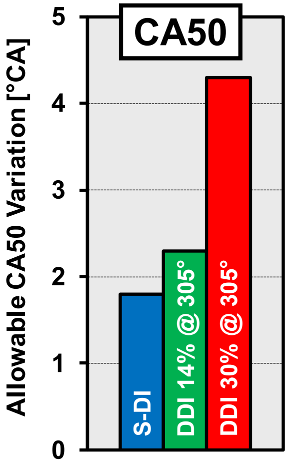
Increasing Robustness with DDI-PFS

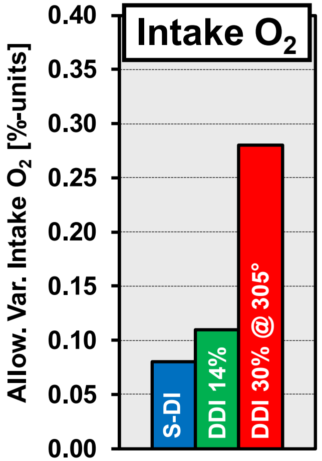
- Our general range of acceptable operation from “knock” to “poor stability” is from RI = 5 MW/m^2 to COV-IMEP$_g$ = 2%.
- Sweep EGR at constant T$_{in}$ to shift CA50 across a wide range for S-DI and DDI.
  $\Rightarrow$ Use intake O$_2$ as a metric for EGR.
- **S-DI-60:** CA50 tolerance = 1.8° CA
  $\Rightarrow$ EGR must vary ≤ 0.08 O$_2$%-units.
- **DDI, 30% at 305°CA:** CA50 tol. = 4.3°CA
  $\Rightarrow$ EGR can vary ≤ 0.28 O$_2$%-units
- DDI-PFS greatly increases tolerance to non-ideal CA50 and EGR levels.

CF-E0, P_{in} = 2.4 bar, T_{in} = 40°C, ϕ_m = 0.4



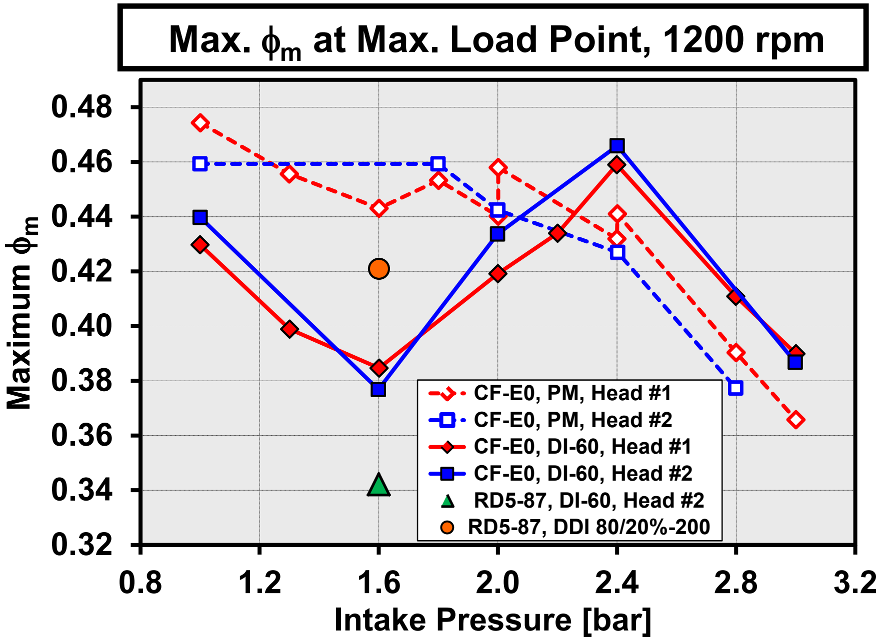


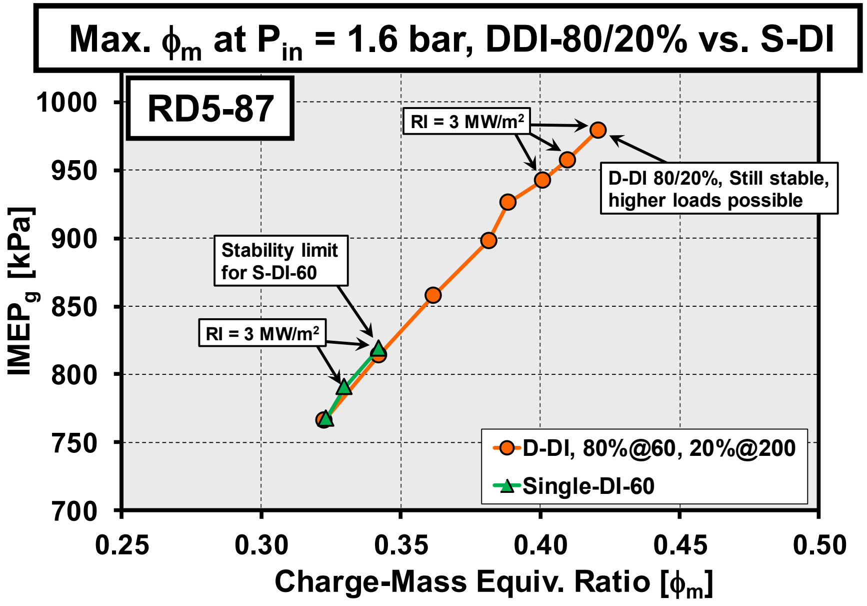




Increasing Stability with DDI-PFS, P_{in} = 1.6 bar

- Both Head #1 and Head #2 show reduced stability for Early-DI (S-DI-60) at P_{in}=1.6 bar ⇒ Cause is not understood.
- Maximum fueling rate (ϕ_m) is significantly reduced compared to PM or S-DI-60 at other P_{in}s.
  - Becomes unstable if ϕ_m is increases, and quickly runs away to knock or misfire.
- With RD5-87, max. ϕ_m with S-DI-60 is even lower than with CF-E0.
- Apply DDI-PFS with an relatively early “late-DI” timing ⇒ 80% at 60° + 20% at 200°CA
- DDI-80/20%-200 greatly increases stability, allowing a substantial load increase. **⇒ ϕ_m increased from 0.34 to 0.42**
- Moreover, still stable at ϕ_m = 0.42, so further increases are possible.
- Even greater increases may be possible with optimization of DDI fueling strategy.





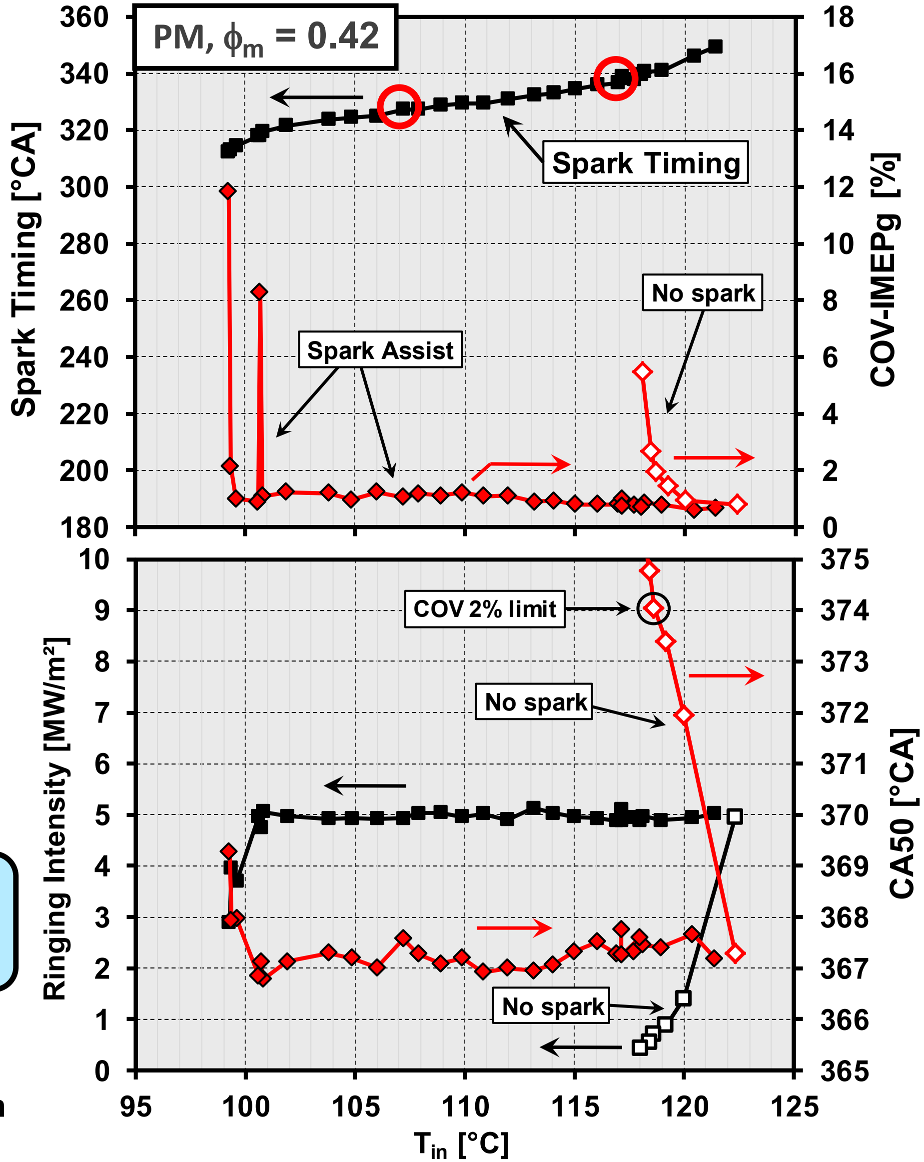
Spark-Assist for LTGC Control, P_{in} = 1 bar

- Spark-assist (SA) is a promising control method, P_{in}=1 bar & lower boost (limit=?)
- Complements injection-timing/PFS control at higher P_{in} ⇒ fuel is ϕ-sensitive

Robustness: ϕ = 0.42, PM fueling

- For CI only (no SA), ΔT_{in} = 3.7°C from RI = 5 MW/m² to COV-IMEP$_g$ = 2%
  - **ΔT_{in} = 3.7°C** gives a ΔCA50 = 7° CA
- For SA + CI, can reduce T_{in} & maintain CA50 and RI by advancing spark-timing.
  - Limited by large cycle-to-cycle variations; COV suddenly becomes >> 2%.
    - > Variability in early-flame propagation
  - **ΔT_{in} = 21°C**
- Spark assist greatly increases tolerance to T_{in} variation, from **3.7 to 21°C.**
- No significant change in CA50, RI, or CE. Slight **decrease in NOx ⇒ lower T_{in}**

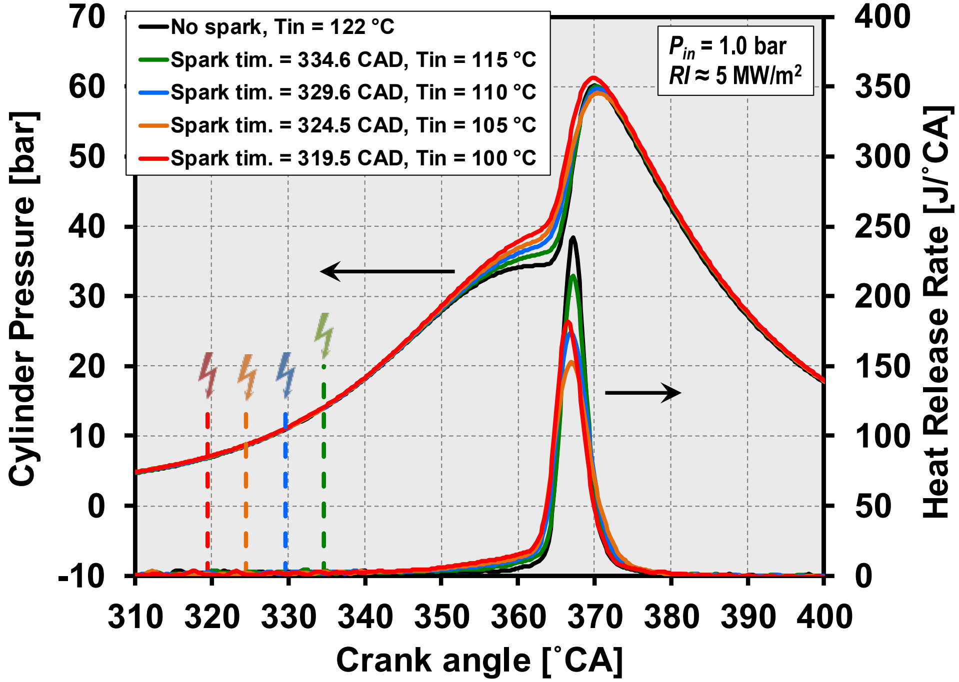
Maintain RI = 5 MW/m² w/ Spark

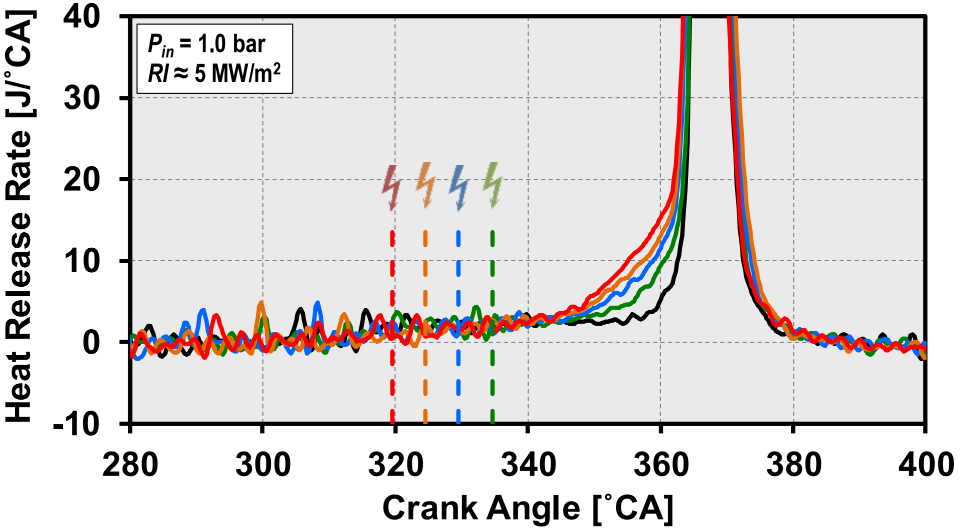


Flame Propagation Effect on HRR, $\phi = 0.42$

- First part of HR associated with flame propagation contributes a significant fraction of the total HR.
  - Up to about 15%
- Compression heating caused by the flame combustion appears to compensate for decrease in T_{in}
  - Effect is similar to the ITHR for boosted operation with CI.

- Can the flame propagation allow CA50 to be retarded further while maintaining robust combustion (COV-IMEPg < 2%)?
- How much control over CA50 does SA provide?



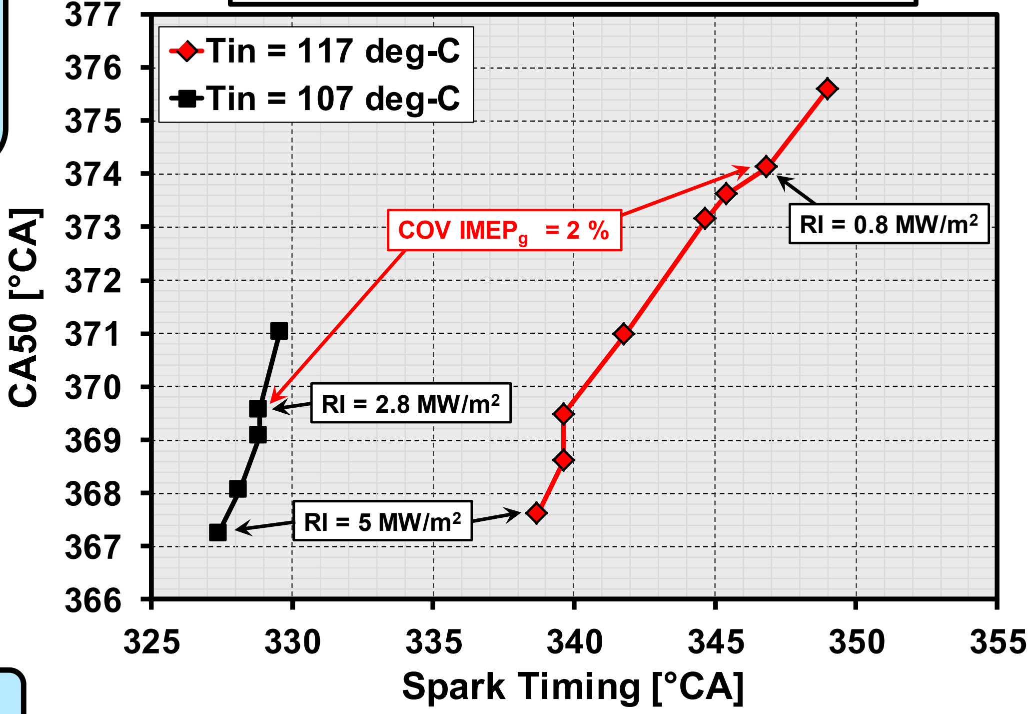


CA50 Control with Spark Assist

- **Spark timing swept at two T_{in}s:**
  - **117°C** ⇒ if no spark, COV-IMEP$_g$ > 5%
  - **107°C** ⇒ if no spark, no combustion
- Retard CA50 by retarding spark timing, from RI = 5 MW/m^2 to COV-IMEP$_g$ = 2%.
- **T_{in} = 117°C:** CA50 **range = 6.5°CA**
  - 0.8° ΔCA50 / 1.0° Δspark-timing
- **T_{in} = 107°C:** CA50 **range = 2.4°CA**
- CA50 range for acceptable SA combustion is smaller for lower T_{in}.
- At these conditions:
  Flame propagation with SA does not allow CA50 to be more retarded than for CI-mode w/o SA (374° CA).
  - **Pure CI-mode, has virtually the same CA50 range = 6.4°CA.**
- But Spark-Assist gives rapid control.

Reminder:
- **T_{in} = 123°C for no spark**, RI = 5
- Lowest T_{in} with spark = 102°C
- Max. CA50 retard w/o spark = 374° CA (limited by COV-IMEPg = 2%)

PM, CF-E0, P_{in} = 1 bar, ϕ_m = 0.42



Collaborations

- Project is conducted in close cooperation with U.S. Industry through the Advanced Engine Combustion (AEC) / HCCI Working Group, under a memorandum of understanding (MOU).
  - Twelve OEMs, Three energy companies, Six national labs, & Several universities.
- General Motors: Bimonthly internet meetings ⇒ in-depth discussions.
  - GM provided 300-bar Bosch HDEV5.1 GDI injector and spark-ignition system.
  - Provide data to GM on boosted LTGC and for modeling PFS-LTGC.
- Cummins, Inc.: Discussions and guidance on working with new low-swirl, spark-plug cylinder heads (Head #2), potential acquisition of Head #3.
- LLNL: Support development and validation of chemical-kinetic mechanism for RD5-87 (87-AKI, E10 gasoline) and related RCM measurements at ANL.

DOE-OVT project is also leveraged through three related research efforts

- Co-Optima Fuels Project: **Funds-in project** of advanced fuels containing a significant renewable fraction for boosted SI and low-T combustion engines.
- Chevron: **Funds-in project** on advanced petroleum-based fuels for LTGC.
- Sandia LDRD: **Funds-in project** on fuel injection.

Future Work

- Continue to focus efforts on combustion-timing control & improved robustness, with an emphasis on lower boost ($1.0 \le P_{in} \le 2.0$ bar).
- Use RD5-87 gasoline (regular E10) for now, and reduce CR to 14:1 ⇒ should increase operating range with RD5-87 and more in-line with OEM targets.
  - Map engine performance for CR = 14:1 w/ RD5-87 (will reduce TE 1.0 – 1.5 %-units)

DDI-PFS with Variable Inj. Timing: ⇒ CA50 control & multiple other benefits

- Determine the range of conditions for which DDI-PFS can be applied effectively ⇒ range of P_{in} (down to 1.3 bar?), fueling rates (ϕ_m), and speed effects.
- Investigate various fueling strategies to improve PFS performance and extend range of application ⇒ vary late-DI timing & fraction, multiple injections, etc.
  - Image fuel distributions in optical engine to guide strategies.
  - Potential of 300 bar GDI injector to improve PFS and its operating range.

Spark-Assisted (SA) LTGC: ⇒ CA50 control, etc.

- Map out range of conditions for effective SA-LTGC with CR = 14:1.
  - Determine benefits at P_{in} = 1.0 bar, and find max. P_{in} for effective SA.
  - Investigate effect of DI fueling and PFS, speed effects, potential to extend load.

Continue to support of LTGC/HCCI modeling: Provide data, analysis, and discussions to support kinetic modeling at LLNL, and CFD modeling at GM.

Summary

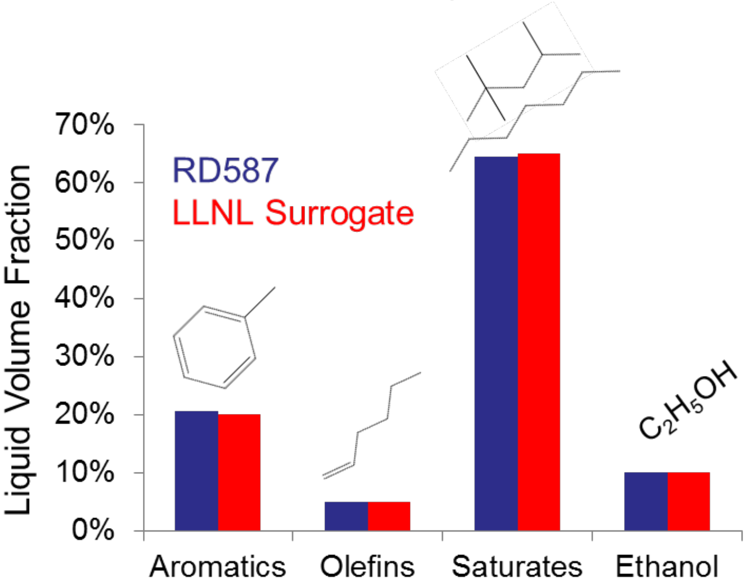
- A new spark-plug capable, low-swirl cylinder head has been installed, and it's combustion performance characterized.
  - Overall performance is similar to previous head, with two exceptions:
    1) For PM fueling, TE is lower by 0.2 – 1.0%-units, due to increased heat transfer.
    2) For early-DI fueling, TE is also reduced at low and high fueling rates due to reduced combustion efficiency caused by less complete fuel/air mixing.
  - High-load limits and CNL are similar for both heads, both PM & DI fueling, all P_{in}s.
- Both CF-E0 & RD5-87 are ϕ-sensitive for P_{in}s down to at least 1.3 bar, indicating that the benefits of PFS can be obtained ⇒ RD5-87 better at lower P_{in}s.
- Showed injection timing can control CA50 up to 8.6°CA, from strong knock to near misfire, as part of DDI-PFS fueling strategy ⇒ ultra-low NOx & soot.
  - Retard the late-DI timing ➩ increases stratification ➩ advances CA50
- Showed that DDI-PFS substantially increases the allowable CA50 range from knock to near misfire.
  ⇒ It can also increase stability for a significant extension of the load range.
- Spark-Assist was found to be effective for CA50 control & increased T_{in} tolerance for $\phi > 0.36$ at $P_{in} = 1$ bar. ⇒ Complements DDI-PFS, which works $P_{in} \geq 1.3$ bar.
- Collaborated with LLNL on development of a kinetic mechanism for RD5-87 and supported related RCM measurements at ANL, and with GM on CFD modeling.

Technical Backup Slides

Collaboration: Kinetic Mechanism for RD5-87

- RD5-87 is a research-grade 87-AKI, E10 regular gasoline with tightly controlled specifications. ⇒ Representative of market fuels.
- Accurate chemical-kinetic mech. will be valuable for research groups & industry.
- Collaborate with LLNL (W. Pitz & M. Mehl) to support their development of a kinetic mech. for RD5-87, and support related RCM measurements at ANL.
- **SNL:** Engine data recently acquired for RD5-87 for fully premixed operation over a wide range of P_{in} and fueling rates (ϕ_m).
  - Data to be provided to LLNL for mechanism tuning and validation.
  - Provided fuel to ANL for RCM studies.
  - Discussions with LLNL and feedback on mechanism performance for further improvement.
- **LLNL:** Proposed a chemical-kinetic mechanism based on a 5-component surrogate, matching compositional & octane properties. ⇒ will tune and validate based on SNL engine data and ANL's RCM data as available.
- **ANL:** RCM data on RD5-87 autoignition.

LLNL proposed surrogate for RD5-87



From W. Pitz, LLNL