High Efficiency GDI Engine Research with Emphasis on Ignition Systems

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Argonne National Laboratory

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Washington, D.C.

June 10, 2015
Project ID: ACE084

Overview

Timeline

- Project start: FY 2013
- Project end: ongoing

Budget

- Funding in FY13: $400k
- Funding in FY14: $350k
- Funding in FY15: $500k

Partners

- Ford Motor Company
- Sandia National Laboratories
- Oak Ridge National Laboratory
- Convergent Science, Inc.

Barriers

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

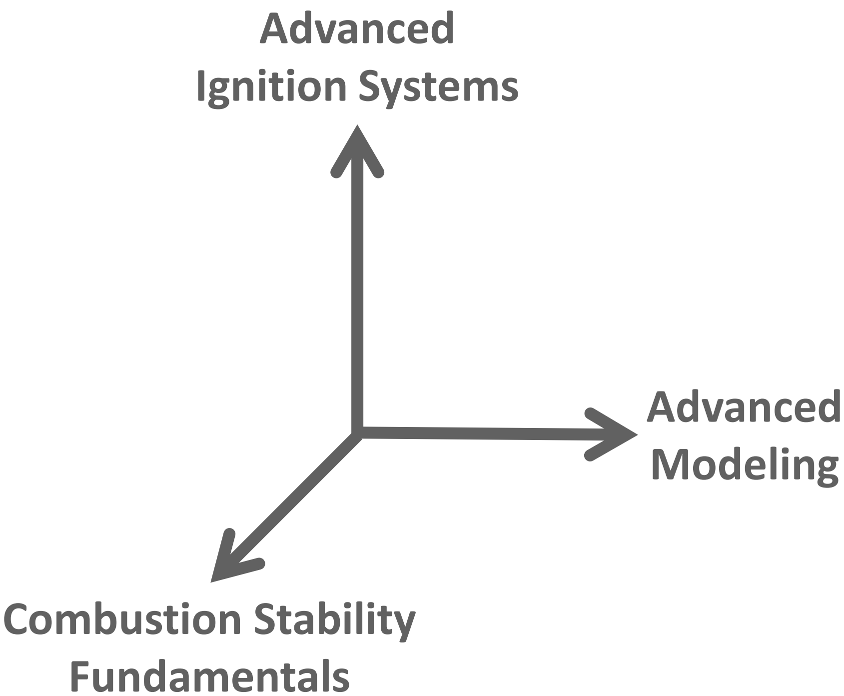
- Limited lean and EGR-diluted operating range
- Lack of systematic assessment of ignition systems and their potential in combination with lean/dilute combustion
- Absence of robust modeling tools

Relevance

- Dilute combustion in advanced gasoline SI engines offers the greatest potential for decreasing petroleum consumption, since gasoline is the most widely produced and used fuel in the US — a trend expected to continue for the foreseeable future[1]
- For the US market, dilute combustion currently translates to stoichiometric operation with ever increasing EGR levels
- Honda R&D recently published achieving 45% BTE using 35% EGR and 450 mJ ignition energy (at 2000 RPM and 8 bar BMEP)[2]
- Recent developments in Solid State Lasers show promise for integration in automotive Spark Ignition (SI) engine applications

[1] US DRIVE Advanced Combustion and Emission Control (ACEC) Technical Roadmap for Light-Duty Powertrains
[2] Ikeya, K., Takazawa, M., Yamada, T., Park, S. et al., "Thermal Efficiency Enhancement of a Gasoline Engine," SAE Int. J. Engines 8(4):2015, doi:10.4271/2015-01-1263.

Project Objectives



Maximize efficiency of automotive gasoline engines through improved dilution tolerance

- Assess advanced ignition systems systematically and determine compatibility with lean/dilute combustion
- Develop robust modeling tools to rapidly screen new designs based on sound metrics
- Research combustion stability issues with the goal to broaden the lean and EGR-dilute operating range

Milestones

Month/Year	Description	Status
March 2014	Meet with Sandia to coordinate collaboration on ignition system projects	Initiated/ ongoing
June 2014	Determine applicability of RANS based 3D simulation approach for flame propagation and combustion stability under dilute (lean/EGR) operating conditions	Completed M1
Sept 2014	Finalize assessment of laser ignition potential	Completed M2
Dec 2014	Compare RANS and LES CFD results in terms of cyclic variability and combustion stability	Completed M3
March 2015	Characterize experimentally and numerically the interaction between the ignition source, the in-cylinder flow, and flame propagation through laser multi-point ignition	Completed M4
June 2015	Stretch goal: Relative increase of 20% in indicated efficiency compared to GDI stoichiometric operation and production spark	On track M5
Sept 2015	Validate ignition model against optical data from Sandia	On track

Approach
Collaborative effort between Labs and OEMs

Classify & Rank Ignition Systems

Jet Ignition

Induction Spark

Laser Ignition

Thermal Plasma

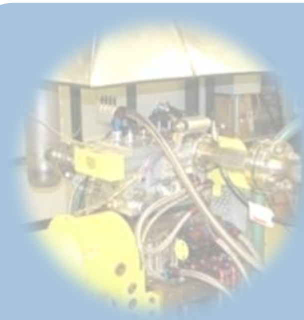
Non-Equ. Plasma

Prioritize based on Literature Review (Sandia/Argonne) and USCAR Input

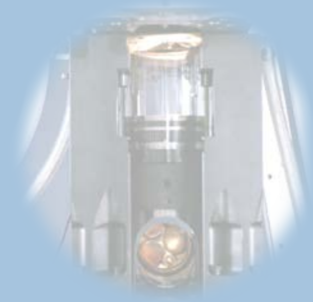
Non-Equ. Plasma

Laser Ignition

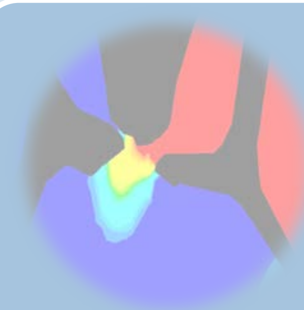
Characterize Ignition System Performance



Metal Engine
- Dilution tolerance
- Efficiency potential
- Emissions signature
- Power requirements



Optical Engine
- Optical diagnostics
- Cylinder sampling with GC analysis
- Kinetics modeling



Simulation
- Develop advanced ignition models
- Propose optimized configurations

Argonne NATIONAL LABORATORY

Sandia National Laboratories

OAK RIDGE National Laboratory

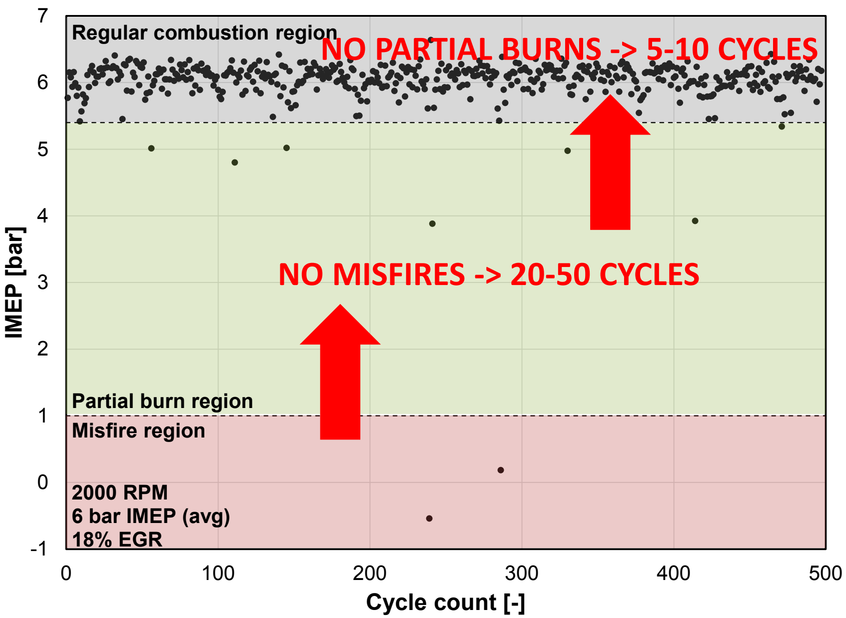
Collaborative Analysis

USCAR

Statistical evaluation of multi-cycle experimental data

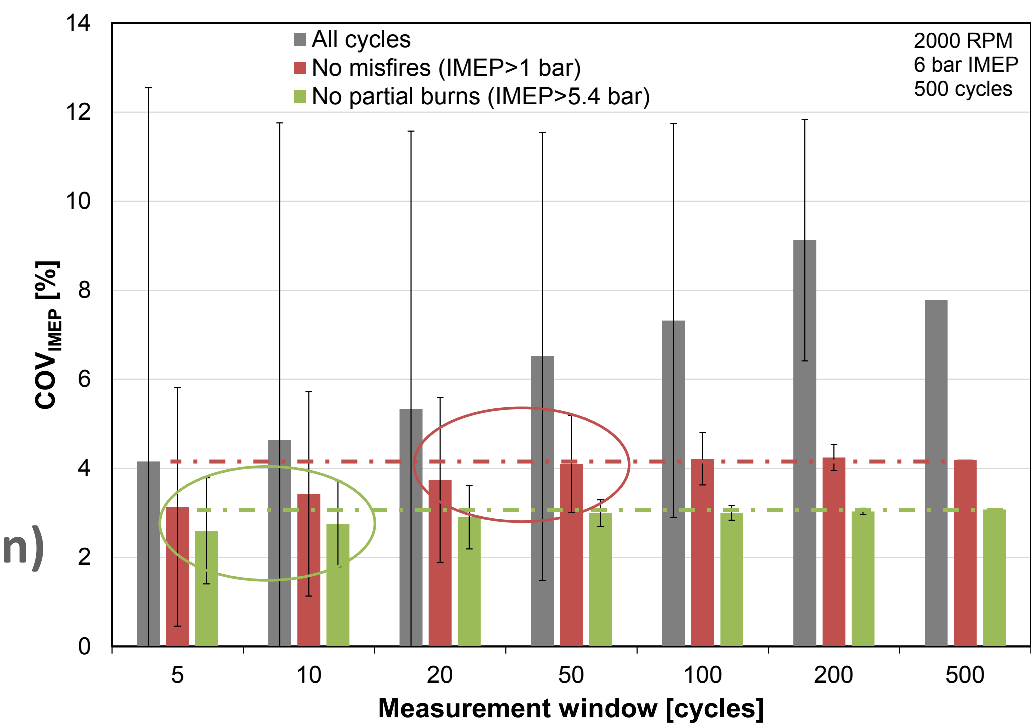
M1

Established minimum cycle number for stability assessment



IMEP range divided in 3 zones

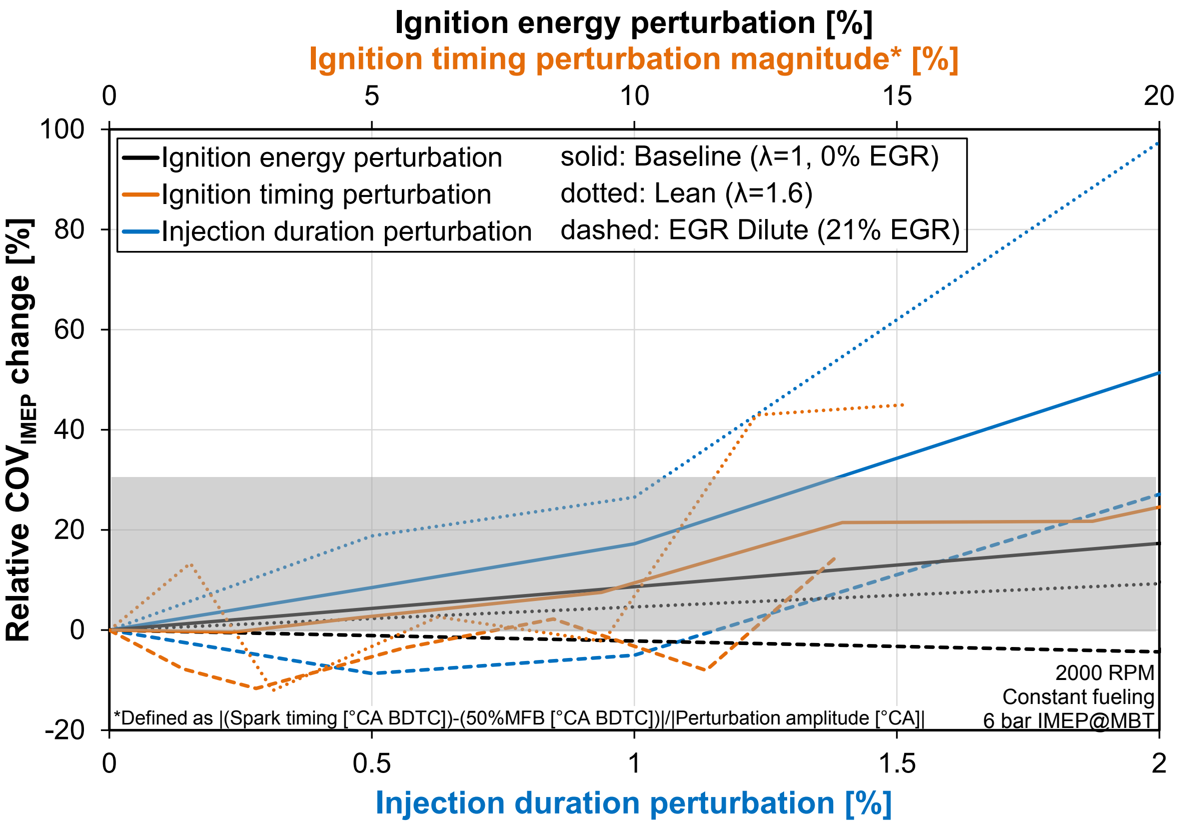
- Regular combustion region (IMEP > 90% of average)
- Partial burn region (1 bar < IMEP < 90% of average)
- Misfire region (IMEP < 1 bar)



COV_{IMEP} can be characterized with as low as 5-10 cycles (regular combustion) and 20-50 cycles when expecting partial burns

M1

Experimental evaluation of stability implications
Perturbation to determine impact of experimental variability



Ignition energy, ignition timing and injection duration perturbation evaluated against 'natural' variability

Lean cases more sensitive to perturbation than baseline and EGR

Relative change in COV$_{IMEP}$ below 30% if:

- Ignition energy perturbation below 20%
- Ignition timing perturbation below 10%
- Injection perturbation below 1%

→ Constant ignition energy, ignition timing and injection duration used for simulations

Wallner, T.; Sevik, J.; Scarcelli, R.; Kaul, B.; Wagner, R., ***Effects of Ignition and Injection Perturbation under Lean and Dilute GDI Engine Operation***. Accepted for publication at the 2015 JSAE/SAE Powertrain Fuels & Lubricants Meeting .

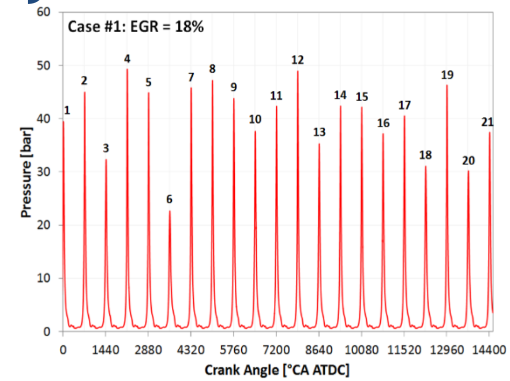
M1

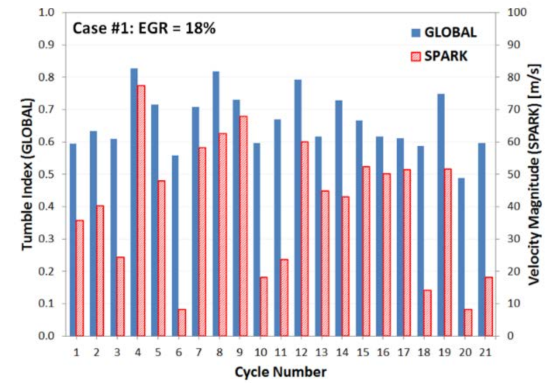
Simulation validation

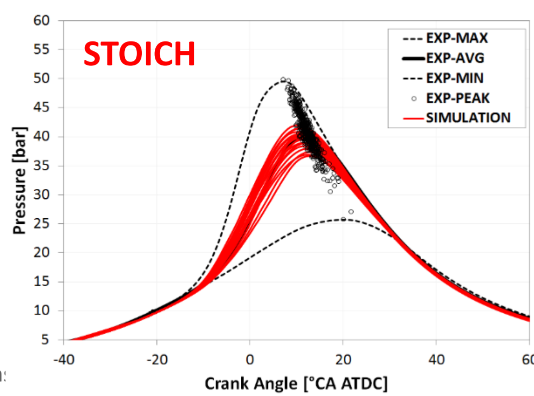
Established RANS as a tool for combustion stability assessment

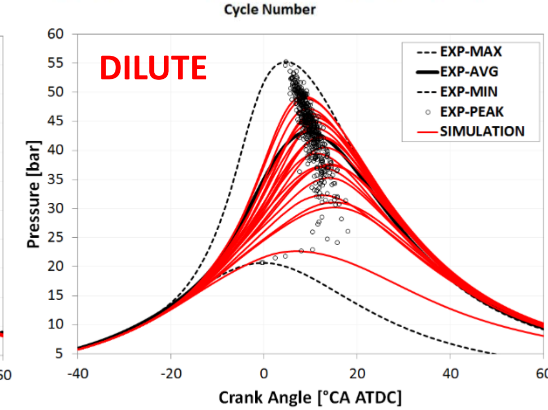
- **Multi-cycle RANS shows cycle-to-cycle variability (CCV)**
  - RANS modeling does not suppress CCV
  - RANS CCV is a **physical effect** of the variability of the **in-cylinder flow** from cycle-to-cycle
  - CCV is an **intrinsic** feature of **unsteady** simulations
  - CCV **is NOT** due to the Adaptive Mesh Refinement (AMR)

- **Multi-cycle RANS validated against experimental data**
  - **Matches** engine data
  - **Captures** the effect of combustion enhancements (ignition properties)
  - **Predicts** combustion stability (qualitatively)
    - **2000 RPM – 6 bar IMEP**
    - **Stoichiometric and Dilute**









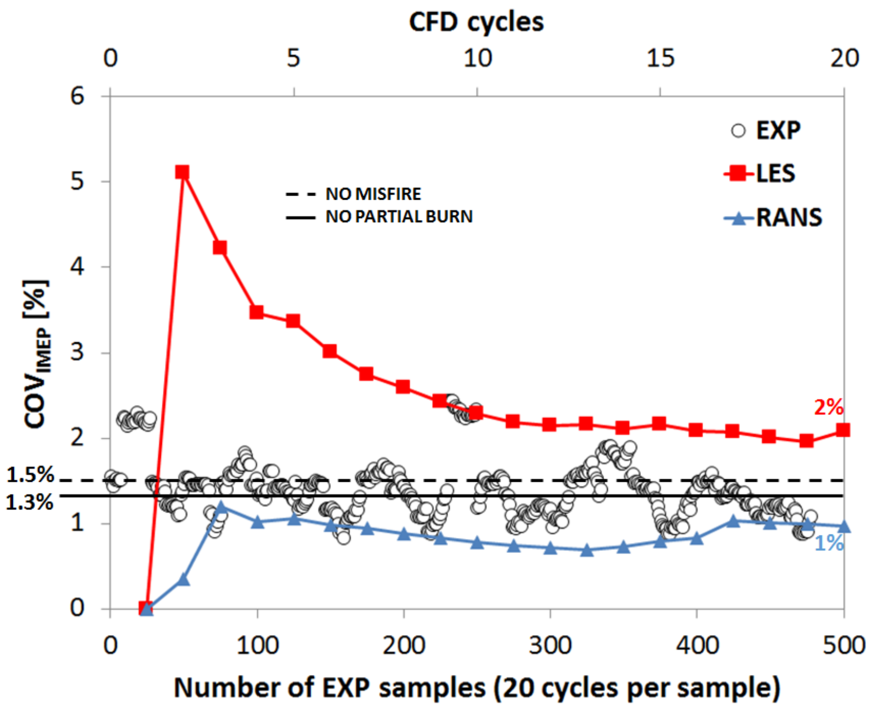
M3

Simulation validation
Evaluated RANS compared to LES results

- Same number of cores (48), same base grid, embedding, AMR → Similar Cell count
- Start from validated RANS → k-ε RNG replaced with LES Dynamic Structure Model

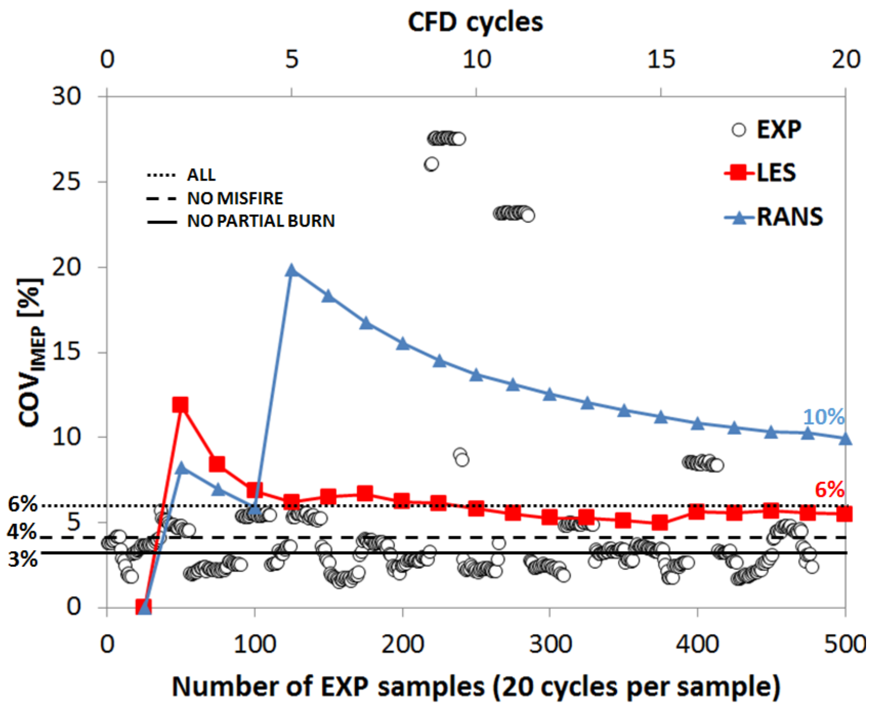
Stoichiometric operation
(low experimental COV_{IMEP})

- Increased CCV and COV_{PMAX} with LES
- Higher predicted COV_{IMEP} with LES



Dilute operation
(high experimental COV_{IMEP})

- Similar CCV and COV_{PMAX}
- Better prediction of COV_{IMEP} with LES



M3

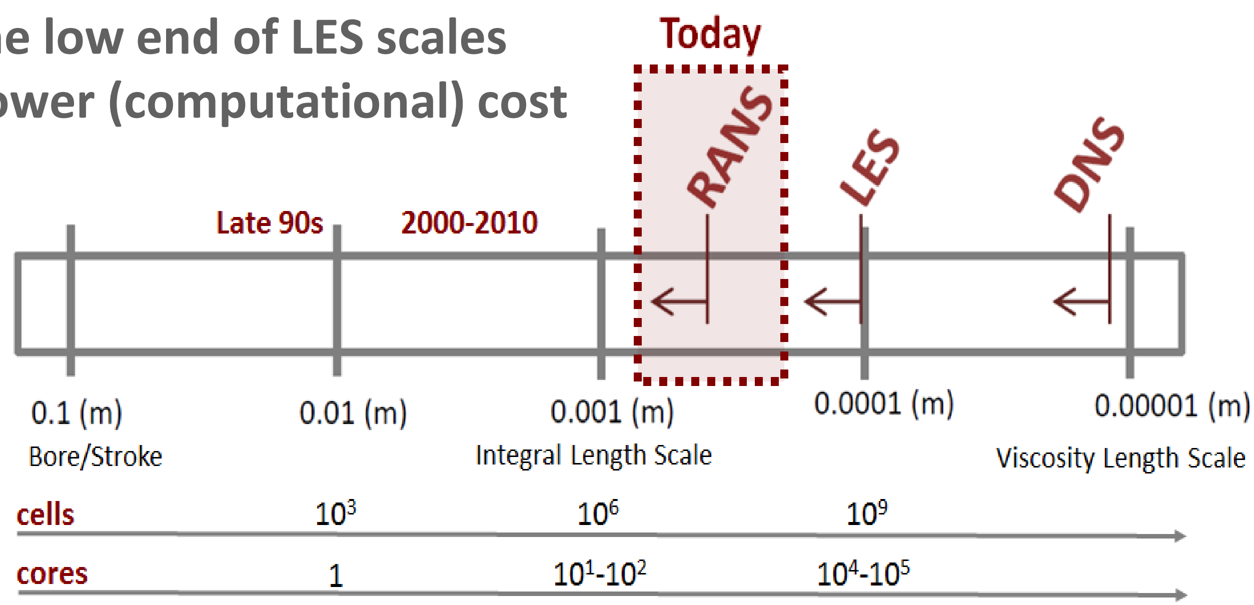
Simulation validation

Evaluated RANS compared to LES (computational) cost

- COV_{IMEP} can be estimated with as low as 20 cycles (not taking misfires into account)
- Perturbation experiments suggest that minor variabilities in injection and ignition event do not significantly alter stability results
- Same-grid LES only slightly improves CCV predictions in 20 vs 20 (CFD vs EXP) cycle comparison (comparing "fine RANS" to "coarse LES" *)
- Further improvement is expected running finer LES
- ANL pioneering ICE large-scalability (max 50 million cells - max 4000 cores**) but still does not fully reach the low end of LES scales
- RANS can capture CCV at lower (computational) cost

* **K. Richards et al.** "The Observation of Cyclic Variation in Engine Simulations when using RANS Turbulence Modeling" **ASME ICEF 2014-5605, 2014**

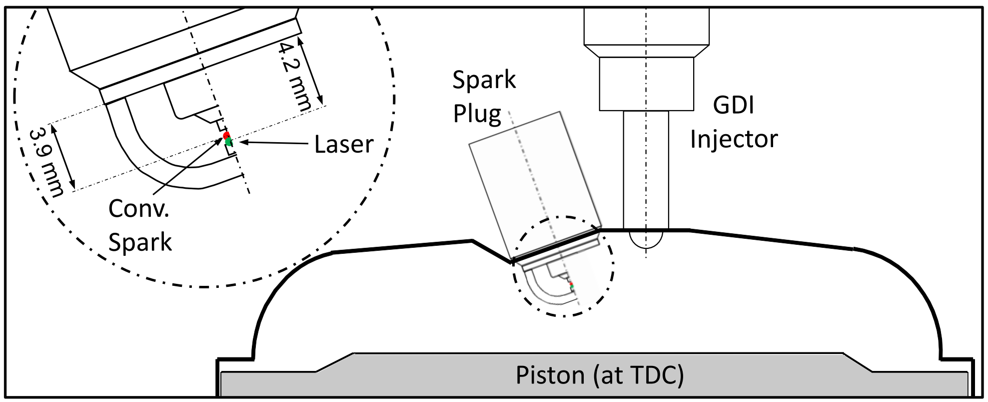
** **S. Som (ANL)** "Advancement in Fuel Spray and Combustion Modeling for Compression Ignition Engine Applications" **ACE075 2015**



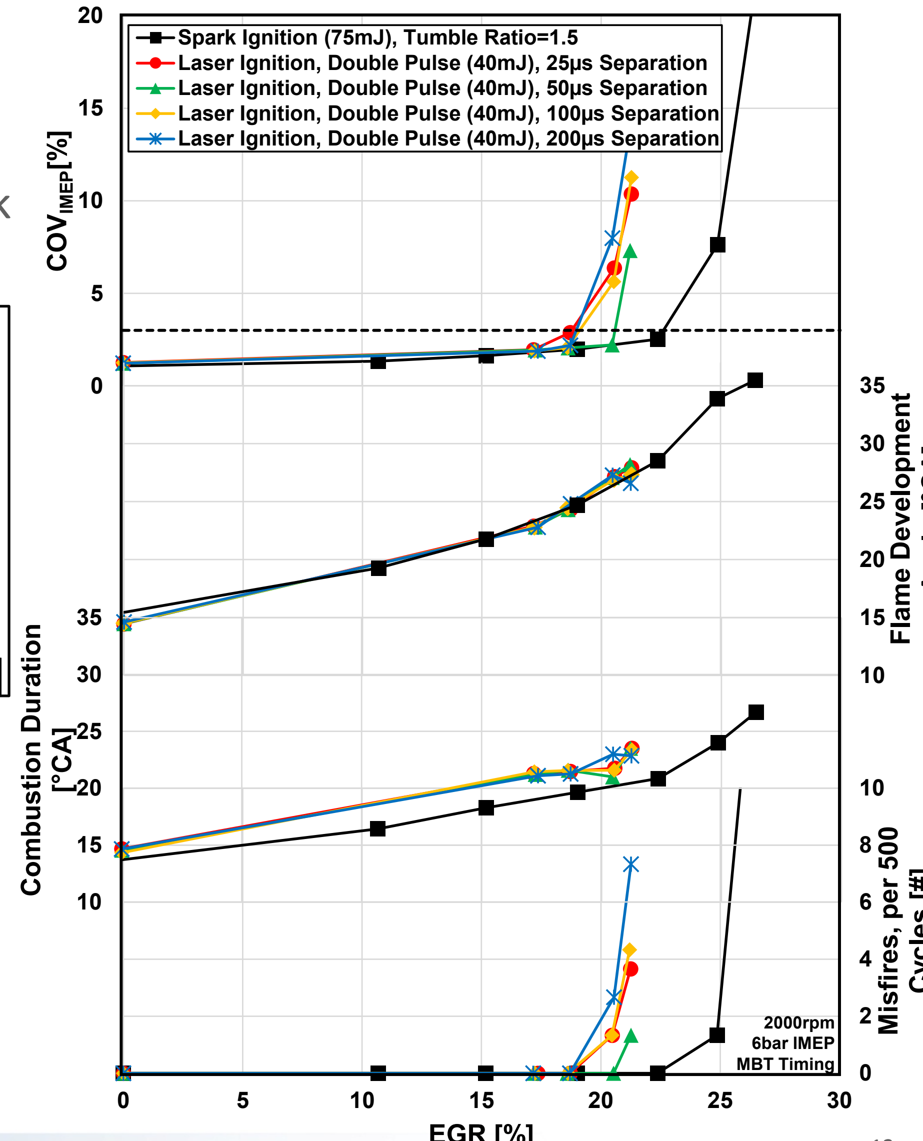
M2

Ignition system characterization
Experimental laser ignition assessment

- **Free-air laser setup**
  - Research laser is guided into spark plug well using optical mirrors and lenses
  - Laser ignition plug takes the place of the spark plug



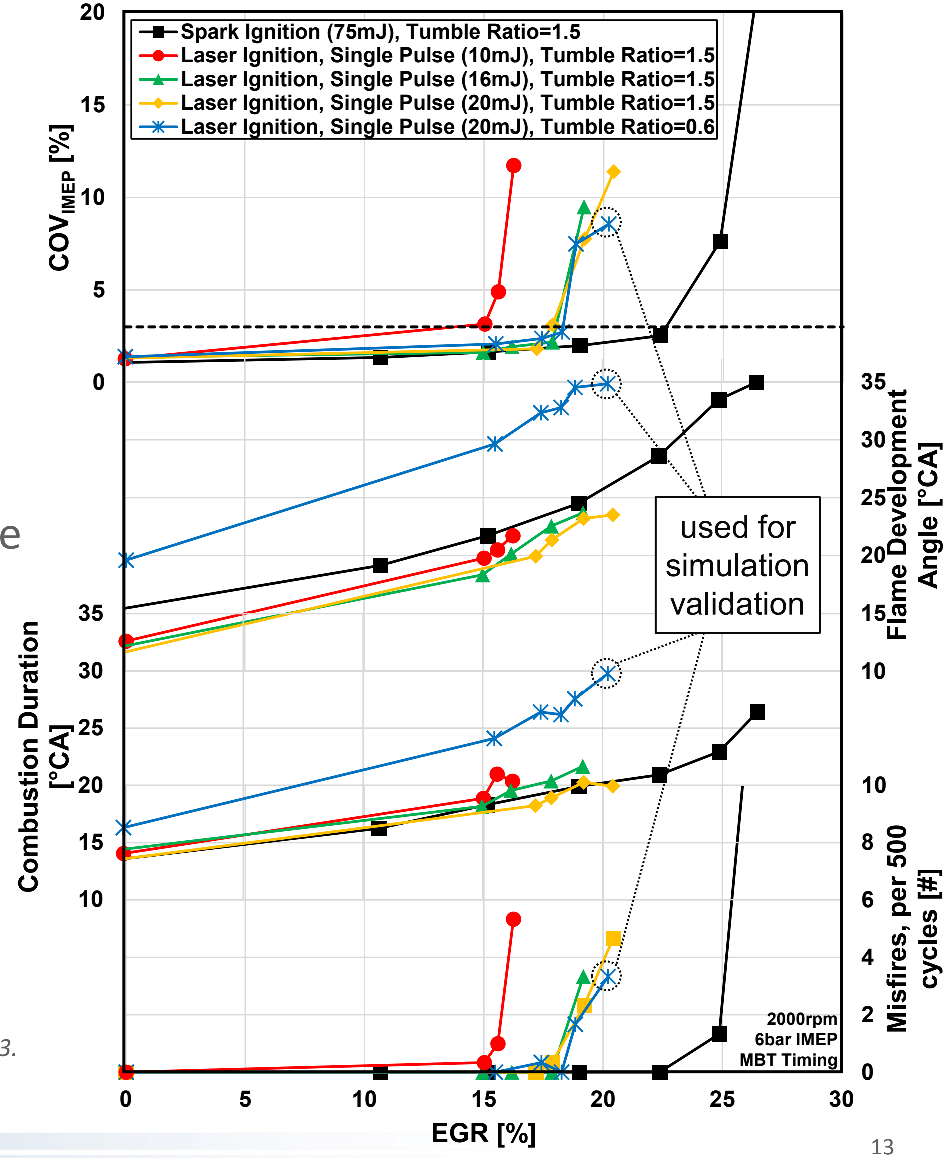
- **Influence of multi-pulse operation**
  - Pulse separation has limited impact on flame development angle and combustion duration
  - 50-100µs pulse separation shows benefits in COV_{IMEP} through reduced number of misfires



M2

Ignition system characterization
Experimental laser ignition assessment

- **Influence of laser energy level**
  - Similar performance once minimum laser energy level is exceeded
  - Tumble ratio influences combustion metrics while stability limit is maintained
- **Results consistent with literature* suggesting that single-point laser ignition in part-load GDI operation…**
  - …does not greatly improve dilution tolerance
  - …reduces flame development angle
  - …maintains combustion duration
- **Results used for laser ignition simulation validation and as impetus to evaluate multi-point laser ignition**



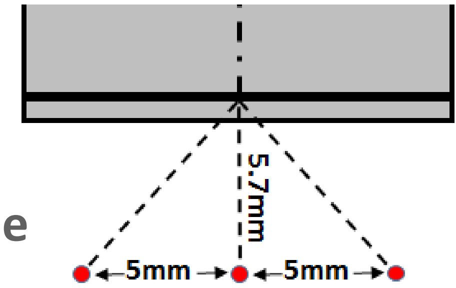
* *Groß, V., Kubach, H., Spicher, U., Schießl, R. et al., "**Influence of Laser-Induced Ignition on Spray-Guided Combustion - Experimental Results and Numerical Simulation of Ignition Processes**," SAE Technical Paper 2009-01-2623, 2009, doi:10.4271/2009-01-2623.*

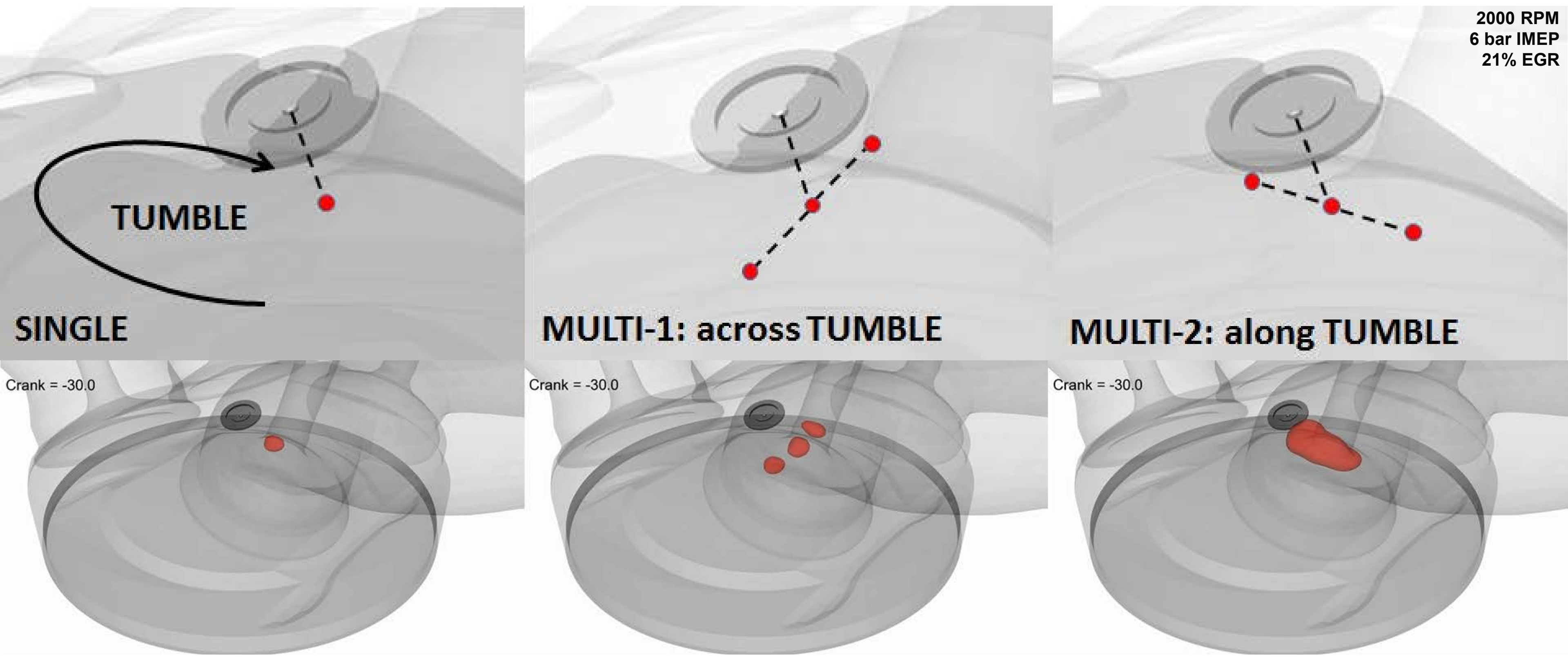
M4

Interaction between ignition and flow

Simulation of multi-point laser ignition

- Feasible design for multi-point laser setup developed
- 1/3 of the total laser energy deposited in each point
- Two configurations evaluated compared to single-point baseline

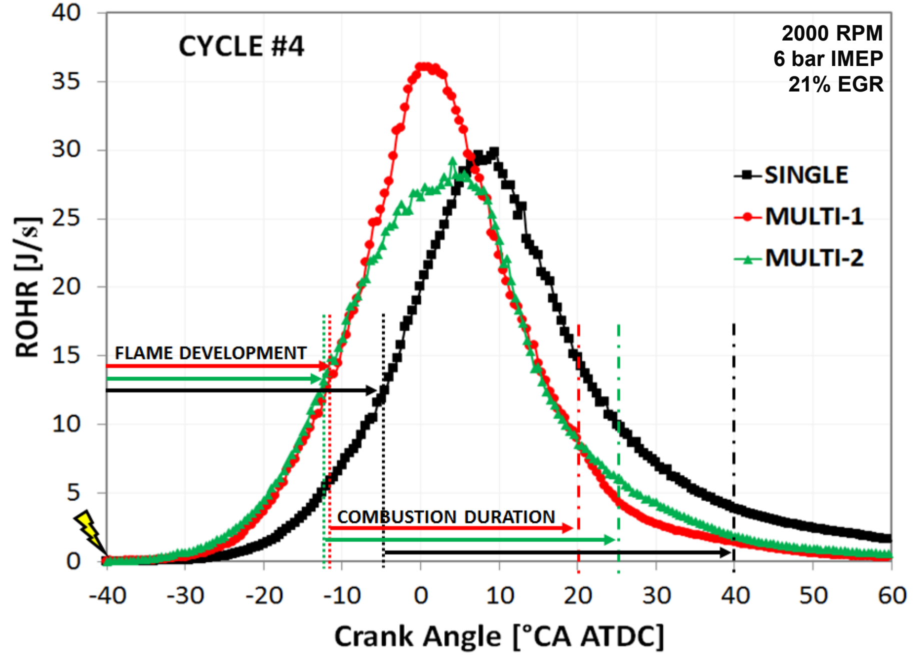


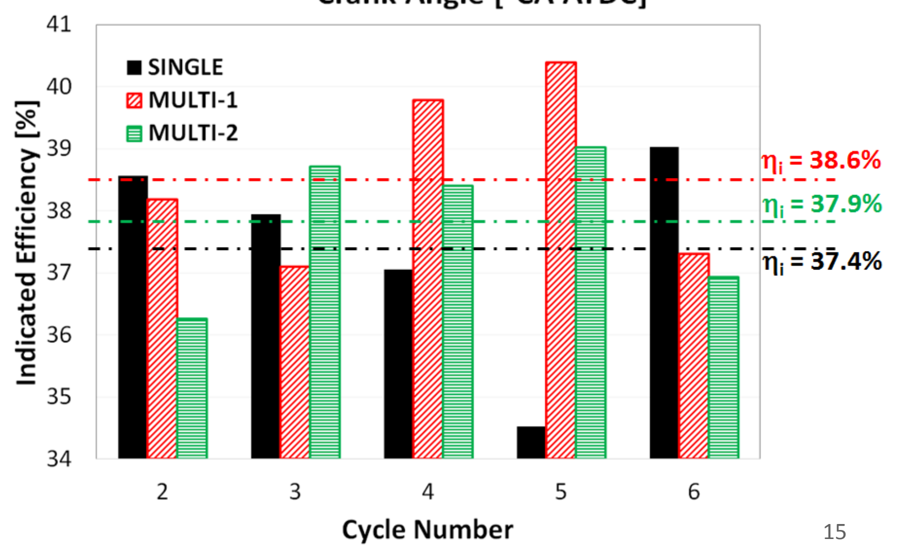


M4

Interaction between ignition and flow
Simulation of multi-point laser ignition

- **Analysis of representative cycle suggests that multi-point laser ignition results in…**
  - ~20% shorter flame development angle
  - ~30% shorter combustion duration
- **'across TUMBLE' configuration (MULTI-1) results in shorter combustion duration than 'along TUMBLE' (MULTI-2)**
- **Multi-cycle simulations suggest…**
  - 1.2% (abs.) indicated efficiency improvement over single-point laser ignition
  - reduction in COV_{IMEP} from ~5% with single-point laser to ~3% with multi-point laser
- **Potential for further improvements with…**
  - adjusted combustion phasing
  - increased charge motion and increased dilution levels
  - additional optimization of multi-point laser ignition location

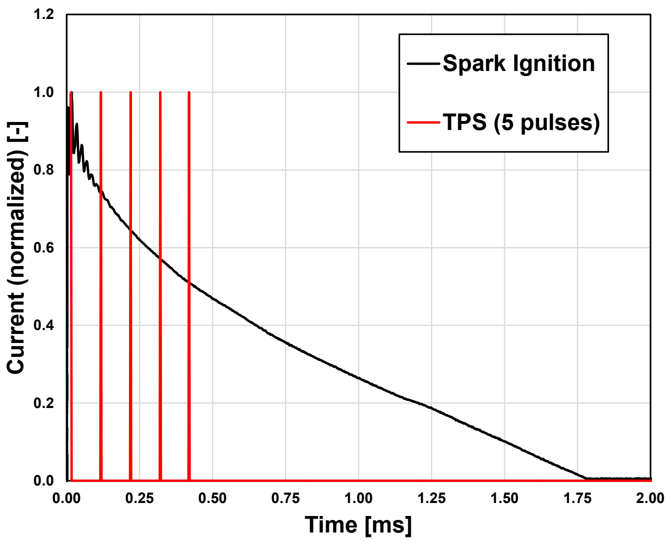




M5

Ignition system characterization
Non-equilibrium plasma system

- **Ignition system concept**
  - Ignition by introducing a sequence of extremely short high-current pulses
  - Up to 20 pulses with 50 ns duration
  - Molecules are dissociated through electron impact instead of heating the surrounding gas
  - Higher density of free radicals leads to a higher rate of branching reactions
- **Concept developed by University of Southern California with TPS as a spin-off company**
- **Current system runs off of laboratory grade power supply**



Conventional Spark Plug (0.7mm gap axial direction)

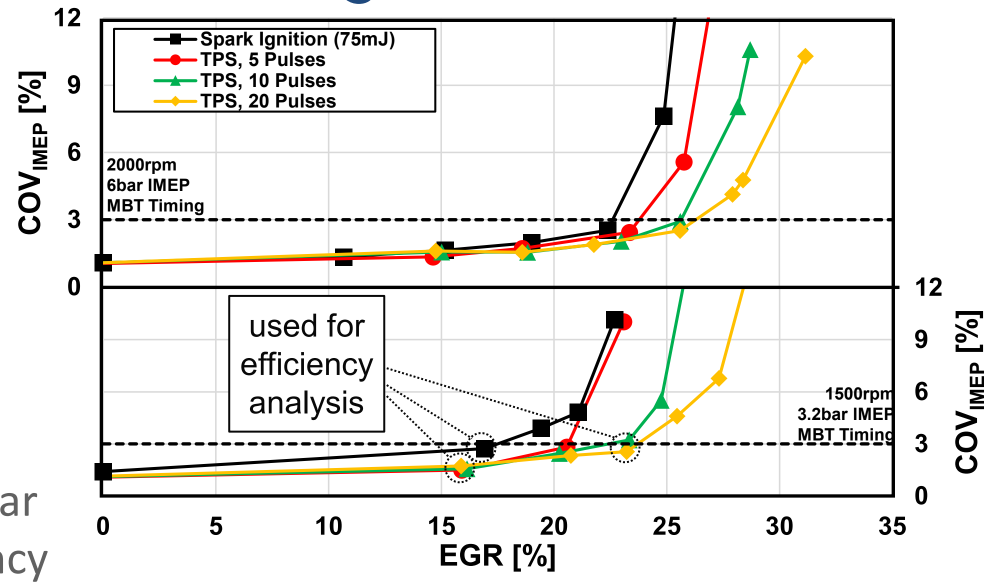
Transient Plasma Plug (2.5mm gap radial direction)

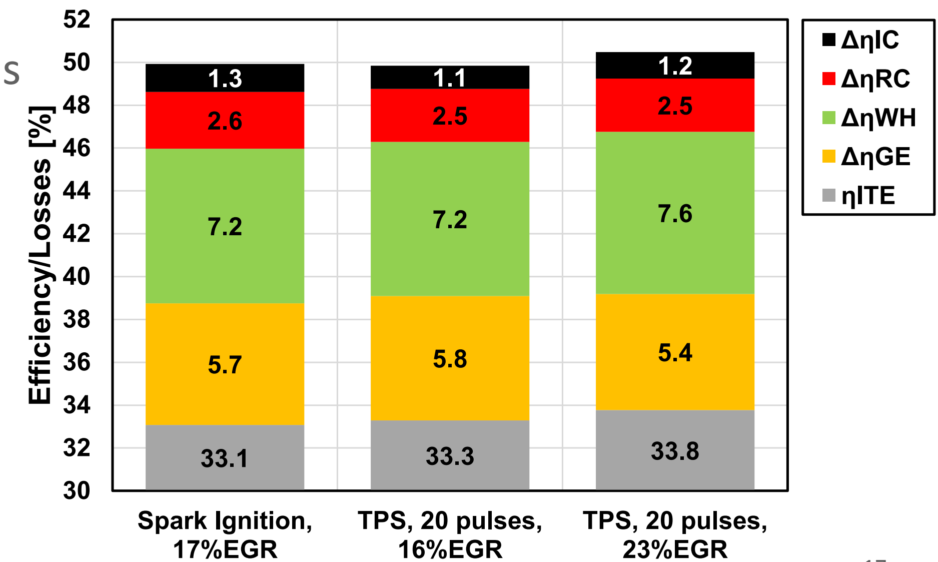
M5

Ignition system characterization

Non-equilibrium plasma path towards stretch goal

- **Non-equilibrium plasma improves dilution tolerance dependent on…**
  - …type of diluent (EGR dilute versus lean)
  - …operating conditions
  - …number of pulses
- **Non-equilibrium plasma compared to conventional spark results in…**
  - …6% improvement in EGR tolerance at similar stability levels improving theoretical efficiency
  - …reduced losses due to incomplete combustion ($\Delta\eta_{IC}$) even at higher dilution levels
  - …similar losses due to real combustion ($\Delta\eta_{RC}$) including combustion phasing and duration
  - …increased wall heat losses ($\Delta\eta_{WH}$) and reduced gas exchange losses ($\Delta\eta_{GE}$) at higher dilution levels due to reduced throttling
  - …0.7% (abs.) increase in indicated efficiency





Responses to previous year reviewers' comments

- **RANS or LES for combustion stability**

✓ CCV demonstrated to be an intrinsic feature of multi-cycle engine simulations (RANS or LES)
✓ Performed comparative evaluation of RANS and LES simulations
✓ RANS provides good accuracy with reduced (computational) cost

- **Overlap/Interaction with ACE006 project led by Isaac Ekoto (SNL)**

✓ Continued close collaboration with Isaac reflected in upcoming milestones
✓ Recent review of respective projects by USCAR ACEC Tech Team concluded that activities are well aligned (including FT006 led by Magnus Sjoberg)

- **Limited laser ignition data**

✓ Expanded experimental evaluation of laser ignition to include energy level and number of pulses with results consistent with literature data
✓ Validated 3D-CFD simulations used to evaluate potential of multi-point laser ignition

- **Perturbation analysis to be developed and improved**

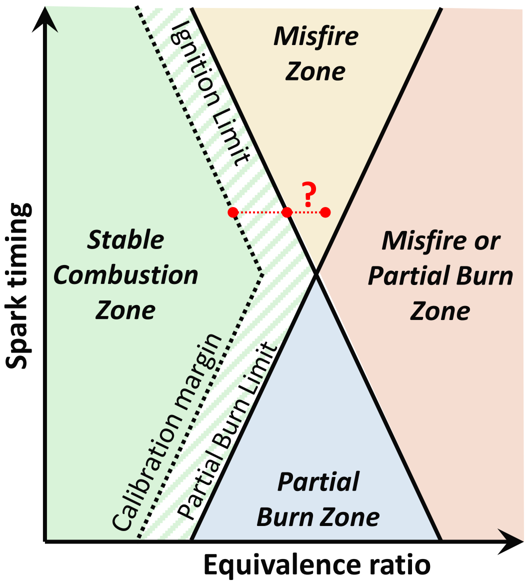
✓ Perturbation experiments expanded to include ignition energy with analysis focus on evaluating 3D-CFD simulation assumptions
✓ Joint publication with Oak Ridge National Laboratory further evaluating perturbation data results with respect to dilute operation stability

Collaboration with other institutions

- **Ford Motor Company**
  - Engine hardware support
  - Project guidance with regular conference calls
- **Sandia National Laboratories**
  - Fundamental ignition/combustion optical analysis
  - Participation in project conference calls with Ford Motor Company
- **Oak Ridge National Laboratory**
  - Data sharing and joint analysis of perturbation result
  - Joint publication
- **Convergent Science, Inc.**
  - Collaboration and joint publications on multi-cycle RANS approach
- **Ignition system developers**
  - Transient Plasma Systems, Inc.: Non-equilibrium plasma ignition system
  - Princeton Optronics, Inc.: Micro-laser hardware (SBIR)
- **USCAR Advanced Combustion & Emissions Control Tech Team**
  - Coordination and update presentations
  - Development of advanced ignition system evaluation guidelines

Remaining challenges and barriers

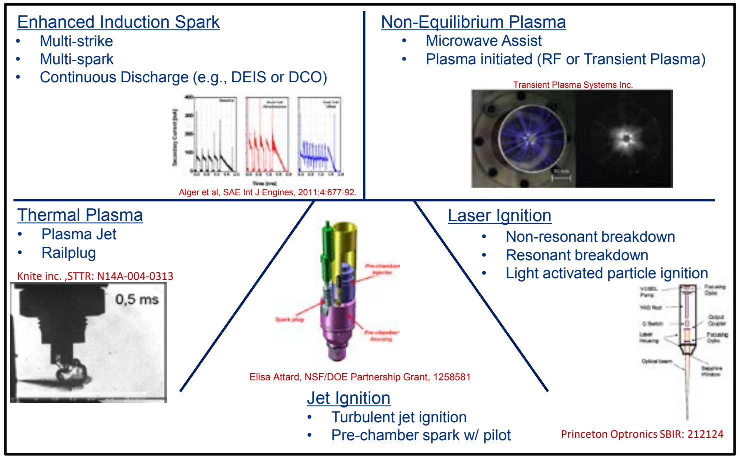
- **Absence of consistent evaluation guidelines for advanced ignition systems**



  - How to evaluate potential of advanced ignition systems for expanding dilute operating regime?
  - Can advanced ignition systems be an enabler for advanced combustion modes?

- **Systematic evaluation of advanced ignition systems**
  - Down-sizing potential of laser ignition systems?
  - Multi-point laser ignition (spatial) and multi-pulse laser ignition (temporal) to mitigate short plasma duration?
  - Plasma jet ignition?
  - Non-equilibrium plasma?

- **Comprehensive ignition modeling approach**
  - Introduce more physics in current ignition models (energy deposition)
  - How to simulate advanced ignition concepts (non-thermal plasma)?
  - How to deal with different chemistry (plasma vs. fuel)?



Courtesy of Isaac Ekoto (ACE006)

Lean limit graph based on '*Quader, A., "**What Limits Lean Operation in Spark Ignition Engines-Flame Initiation or Propagation?**," SAE Technical Paper 760760, 1976, doi:10.4271/760760.*' and '*Kaul, B., Wagner, R., and Green, J., "**Analysis of Cyclic Variability of Heat Release for High-EGR GDI Engine Operation with Observations on Implications for Effective Control**," SAE Int. J. Engines 6(1):132-141, 2013, doi:10.4271/2013-01-0270.*'

Proposed future work - Ignition modeling and validation

Spark Ignition
- Practical model with calibration

Laser Ignition
- Ideal application for energy deposit model

Transient Plasma Ignition
- Non-thermal plasma
- Nanosec. pulsed discharge
- Lower total energy

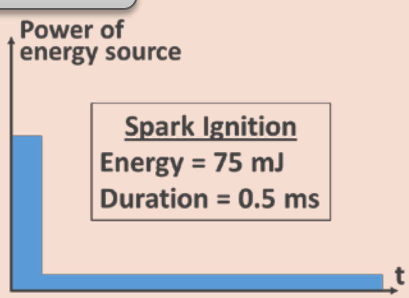
Plasma Jet? Others?

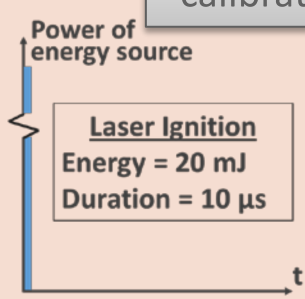
Experimental characterization and validation (coordinated with Isaac Ekoto)

Energy Deposit Model

- Focus on characterizing the external energy source
- Need to calibrate initial kernel size

Amount, Duration, Profile → External energy source → Ignition kernel ⇄ Kernel size calibration





New Concept Ignition Model

- Focus on describing the effect of active species (radicals, ions, etc.) from the transient plasma
- Essential for modeling TPI due to different time scales and energy levels

Plasma region size

Plasma composition

Plasma region temperature and pressure

→ flame

Reaction kinetics

Summary

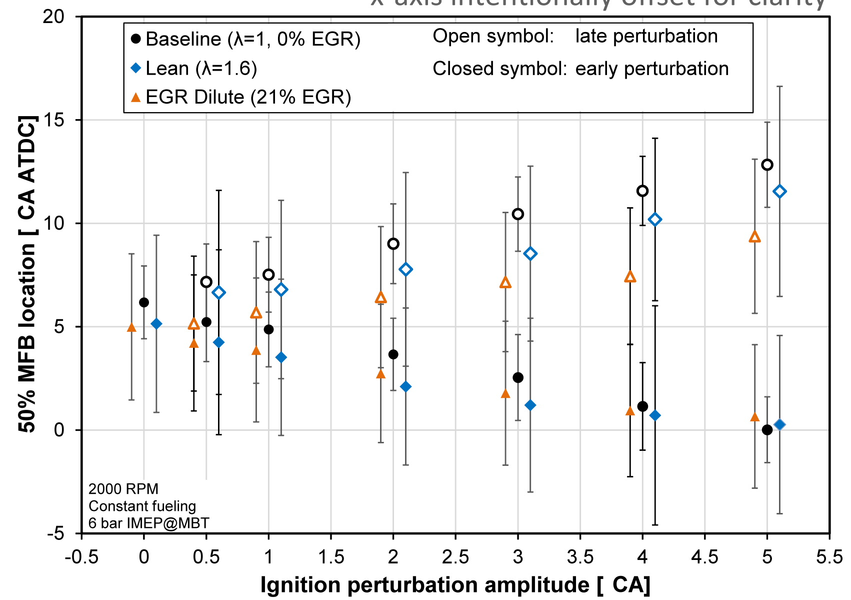
- **Improvements to combustion stability and dilution tolerance are critical to further increasing efficiency potential of gasoline spark ignition engines**
- **Argonne's comprehensive approach combines experimental and simulation tasks with analytical assessment in a concerted effort with Sandia's optical engine work**
- **Technical accomplishments in FY2015 include:**
  - Assessment of perturbation data to support RANS simulation assumptions
  - Validation of multi-cycle RANS approach and evaluation against LES results
  - Experimental and simulation assessment of laser ignition potential
  - Experimental evaluation of non-equilibrium plasma ignition system
- **Targeted collaborations with OEMs, industry and national laboratories ensure relevance of the overall project direction and effective use of resources**
- **Future work has been identified to address the remaining barriers including:**
  - Support the development of comprehensive guidelines to assess advanced ignition systems
  - Develop a comprehensive modeling approach to simulate advanced ignition systems
  - Deliver experimental results to validate simulation models, evaluate the potential of advanced ignition systems and identify areas for further optimization

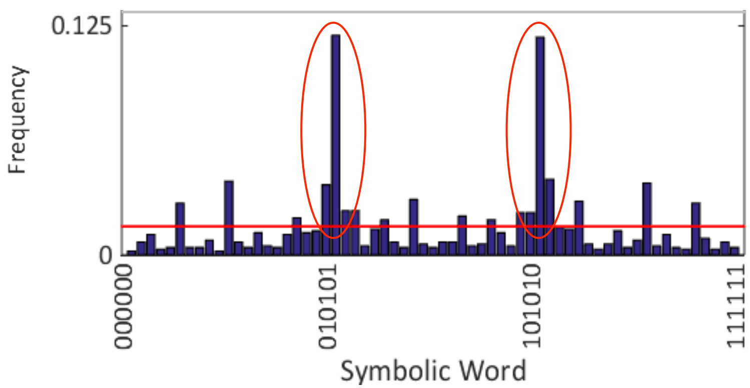
Technical Back-Up Slides

Selective post-process of perturbation results

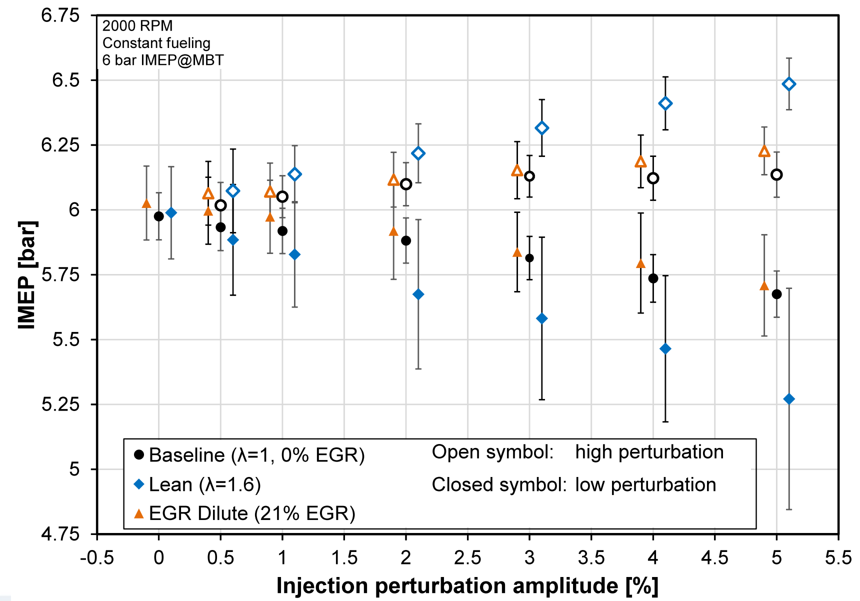
- **Selective post-processing of high/low ignition and injection perturbation data sets suggests that…**
  - …dilution reduces the sensitivity to ignition perturbation attributable to higher natural variability and longer combustion duration
  - …lean operation is very sensitive to injection perturbation, with the effects of perturbations amplified by inherent next-cycle feedback

x-axis intentionally offset for clarity





Symbol sequence analysis of cumulative heat release
2000 RPM, 6 bar IMEP, λ=1.6, 0.5% injection perturbation



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Simulation details

CONVERGE from Convergent Science, Inc.

- **Orthogonal grid with advanced refinement algorithm**
  - ✓ Base grid = 4 mm
  - ✓ Fixed Embedding where needed (chamber, valve seats, spark-plug)
  - ✓ AMR based on Temperature and Velocity gradients
  - ✓ **Cell size during combustion = 0.125 mm (spark) – 0.5 mm (flame)**
  - ✓ High accuracy with reasonably small grids (1,200,000 cells maximum)
  - ✓ One cycle simulated in 60 hrs on 48 cores
- **2nd order accuracy for the momentum equation (central scheme)**
- **RANS approach, k-ε RNG**
- **LES approach, Dynamic Structure Model**
- **Energy deposition model (L-type for spark-based, R=0.25mm sphere)**
- **SAGE Model (direct chemistry) → No Turbulence Chemistry Interaction**
- **Multi-zone model to speed up the calculations involving kinetics**

RANS Cycle-to-Cycle Variability (CCV)

NOT a numerical artifact!

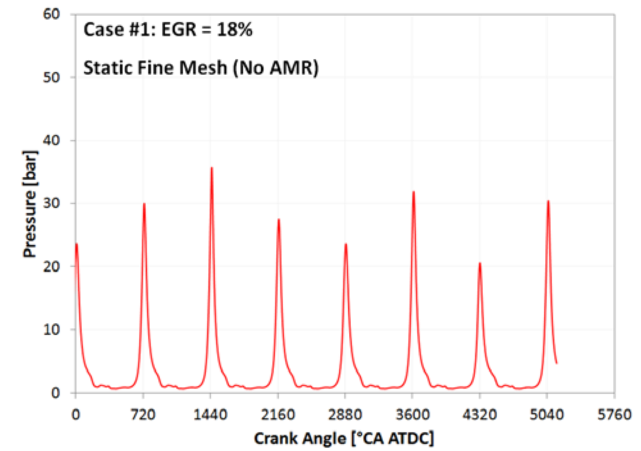
- Due to natural causes (flow variability)
- Not due to Adaptive Mesh Refinement (AMR)
- Static mesh (no AMR) shows CCV as well

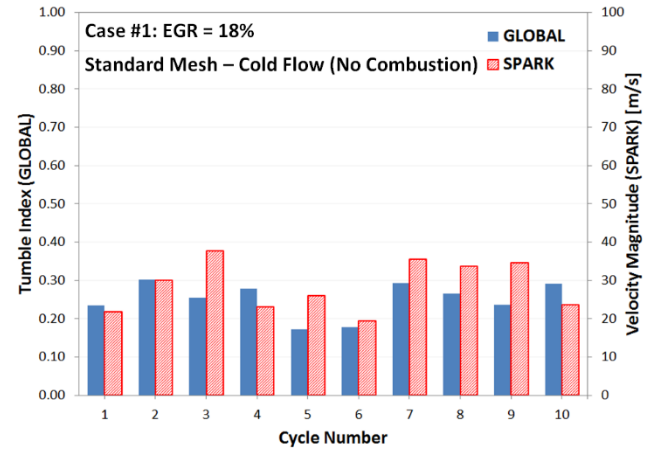
INTRINSIC feature of UNSTEADY simulations

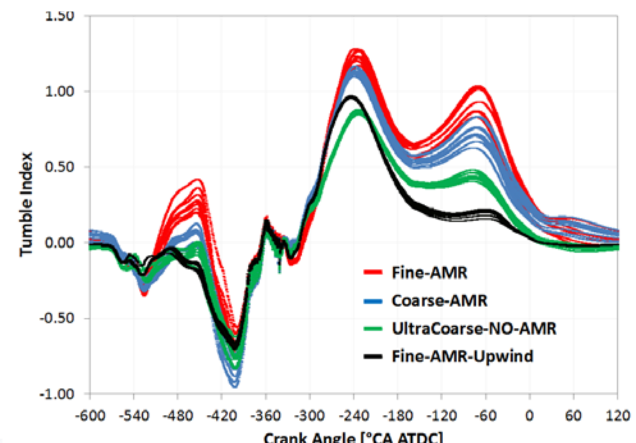
- The cold-flow analysis show converging pressure traces
- Still, the variability of the flow structures is not destroyed
- This variability somewhat affects flame propagation and COULD generate large CCV

Numerical VISCOSITY plays a KEY role

- Reduces accuracy and increases repeatability
- Coarse mesh increases viscosity
- Upwinding increases viscosity
- Conventional high-viscosity RANS suppresses CCV



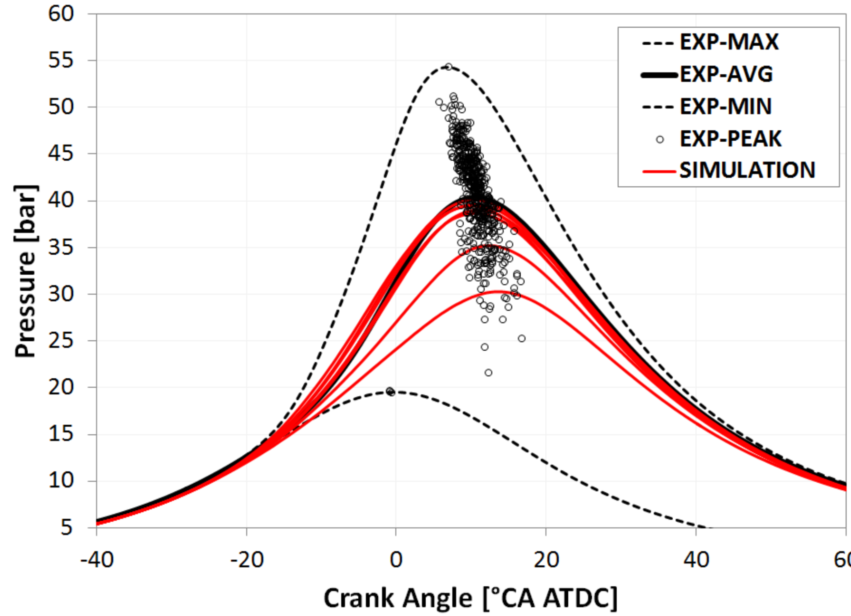




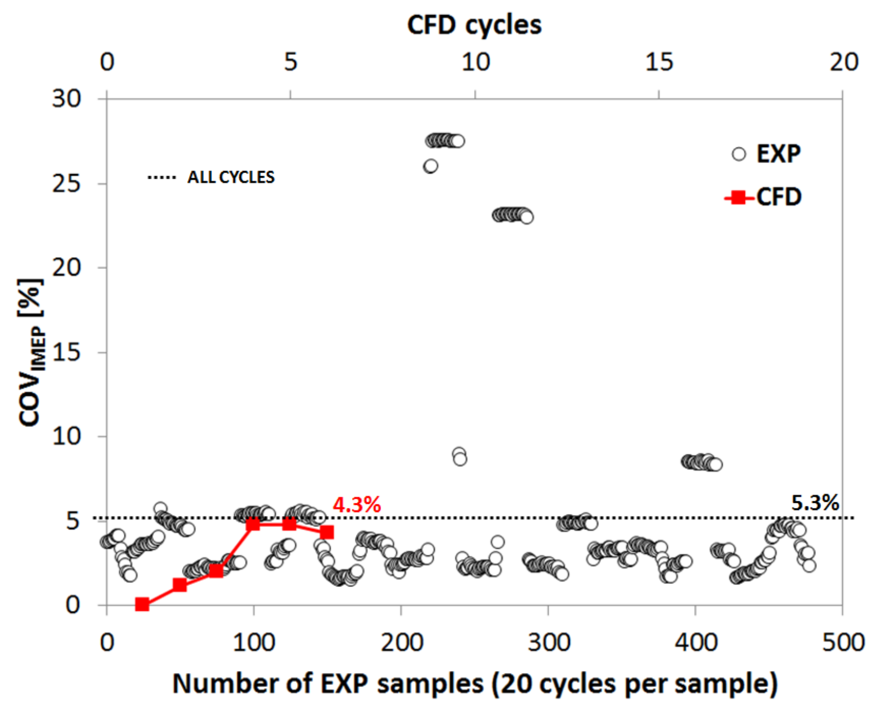
Single-point laser validation

Same ignition model (Energy Deposition) as spark-based ignition system

- Reduced duration (10 µs)
- Constant deposition profile
- Identical initial ignition site properties (sphere R = 0.25 mm)



- **Good qualitative agreement**
- **Most (≈70%) of CFD traces overlap with average experimental data**
- **Slow burning cycles predicted**
- **Additional cycles needed to capture CCV**
- **Good initial agreement with experimental COV_{IMEP}**



Non-equilibrium plasma
Combustion stability analysis

- **Non-equilibrium plasma extended dilution tolerance up to 30% (rel.) compared to conventional spark by…**
  - …shortening flame development angle
  - …maintaining combustion duration
  - …reducing variability in 10, 50, 90%MFB
- **Similar power consumption (1500 RPM)**
  - Spark ignition ~ 10W
  - 5 pulses ~ 10W