Combustion Research Facility

Light-Duty Diesel Combustion

Light-Duty Combustion Experiments

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Light-Duty Combustion Modeling

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Project ID # ACE002

Overview

Timeline:

- Project has supported DOE/industry advanced engine development projects since 1997
- Direction and continuation evaluated yearly

Budget:

DOE funded on a year-by-year basis)

- SNL $800k (FY13), $740k (FY13)
- UW $175k (FY13), $200k (FY13)

Barriers addressed:

A Lack of fundamental knowledge

B, G Lack of cost-effective emission control

C Lack of modeling capability

Technical targets addressed:

- 40% diesel fuel economy improvement
- Tier 2, bin 2 emissions
- Emission control efficiency penalty < 1%
- 30 $/kW power specific cost

(Barriers/Targets from EERE-VT 2011-15 Multi-year plan)

Partners:

- 20 industry/national laboratory partners in the Advanced Engine Combustion MOU
- Close collaboration with GM) and Ford diesel groups)
- Close collaboration with) Convergent Science)
- (Additional post-doc funded by GM

Technical/Programmatic Approach

Objective:
- **Develop a fundamental understanding of the combustion process**
- **Validate and improve computational tools for design**

SNL Optical Engine
- Optical measurements of flow and species
- Emissions and pressure analysis
- Model assessment

DOE & GM funded

GM 1.9 ℓ head/cylinder set

UW Simulations
- Interpretation of experiment
- Model development
- Optimization methodologies
- Numerical studies

DOE & GM funded

Additional 3rd party simulations (Convergent Science)

Programmatic Leverage:
- Closely coordinated program with both modeling and experiments
- Significant leverage of DOE funds by support from other sources
- Focused on an engine platform used by several other research groups (UW, ORNL)
- Input from and technical transfer to industry strongly established

Overview of Technical Accomplishments

- Status March 2013: Analysis of ϕ-distributions and impact on HC/CO using *n*-heptane/*iso*-octane fuel as R_s, P_{inj} and SOI were varied. Development of LIF technique for diesel PRFs (*n-/iso*-cetane)

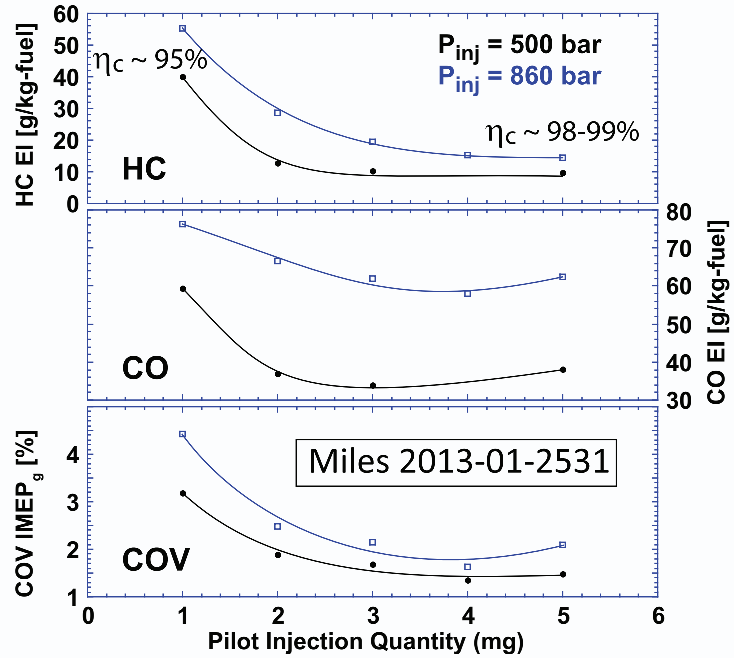
  Progress last 12 Months:

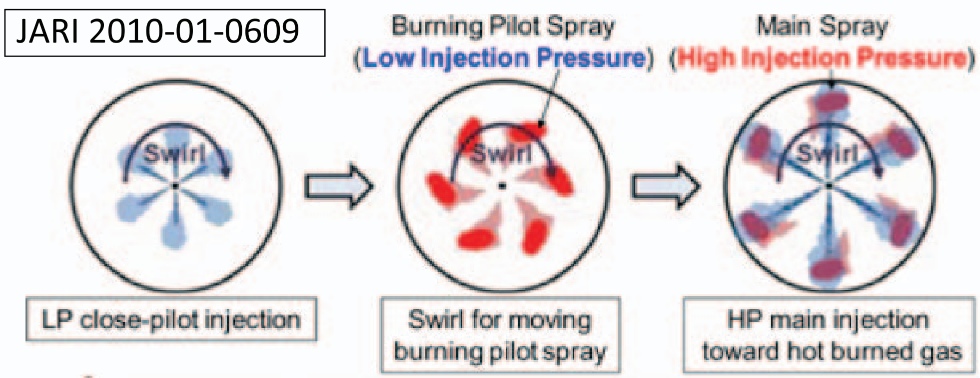
- **Upgraded FIE and Injection Rate Measurement Capability**
  - Upgraded FIE to fast-acting (pressure-balanced) Bosch MultiJet II (Courtesy GM)
  - Acquired/installed Moehwald HDA injection rate analyzer
  - Provided rate measurements to modelers; supported multi-injection studies
- **Pilot Ignition Processes**
  - Experimental database of pilot ignition spanning dilute, LTC conditions through conventional diesel conditions for varying pilot mass, $[O_2]$, T_{amb}, & P_{inj}
  - Measurement and analysis of ϕ-distributions formed using diesel PRFs; Homogeneous reactor simulations of the ignition of DPRF mixtures
  - Assessment of the ability of engineering CFD codes to predict pilot ignition
- **Full induction stroke flow measurements**
  - Developed image distortion correction algorithms to allow separate corrections for each PIV laser pulse; multiple crank angles
  - Initial investigations of full induction stroke at 3 swirl ratios; close collaboration with modelers; improved inlet boundary conditions and throttle plate geometry

Relevance I

- A better understanding of pilot ignition properties is needed to adapt pilot injection strategies to LTC

"Robust" pilot ignition can improve light load HC, CO, noise, & COV with little impact on soot/NOx (see also Honda 2004-01-0113)





At higher loads, pilot strategies can provide good ISFC (185 g/kW-hr), soot/NOx (0.1 /0.16 g/kW-hr), and low noise (dP/dθ ~ 0.5 MPa/°CA)

- Pilot ignition studies under low-temperature conditions support the development of cold-start strategies and cold, *in-cylinder* emission control
- Pilot ignition studies also support model-based control strategies (Mazda Sky-Activ-D) and on-board fuel quality detection (Toyota/Denso i-ART)

Relevance II

- Multiple injection strategies impact soot, NO_X, HC and CO emissions as well as combustion noise. *Trade-offs adopted seeking to balance these factors un-equivocally impact BSFC*
- Flow measurements, accurate injection rate profiles, and improved boundary conditions support the development of a predictive simulation capability

A better understanding of pilot / multiple injections, better control strategies, and better predictive tools directly address EE/OVT technical targets:

- 40% diesel fuel economy improvement
- Emission control efficiency penalty < 1%
- Tier 2, Bin 2 emissions
- 30 $/kW power specific cost

- Bonus:

Diesel pilot timing & strategy can significantly improve lean-NG engine efficiency and stability

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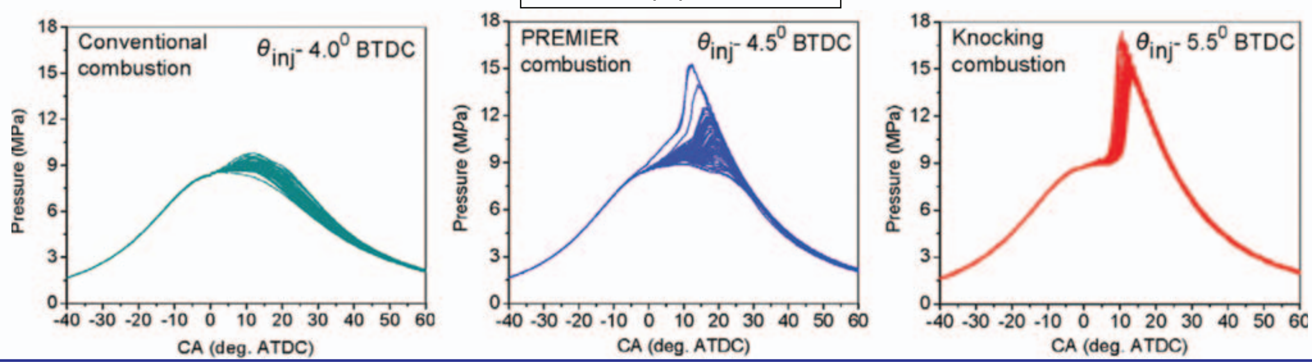
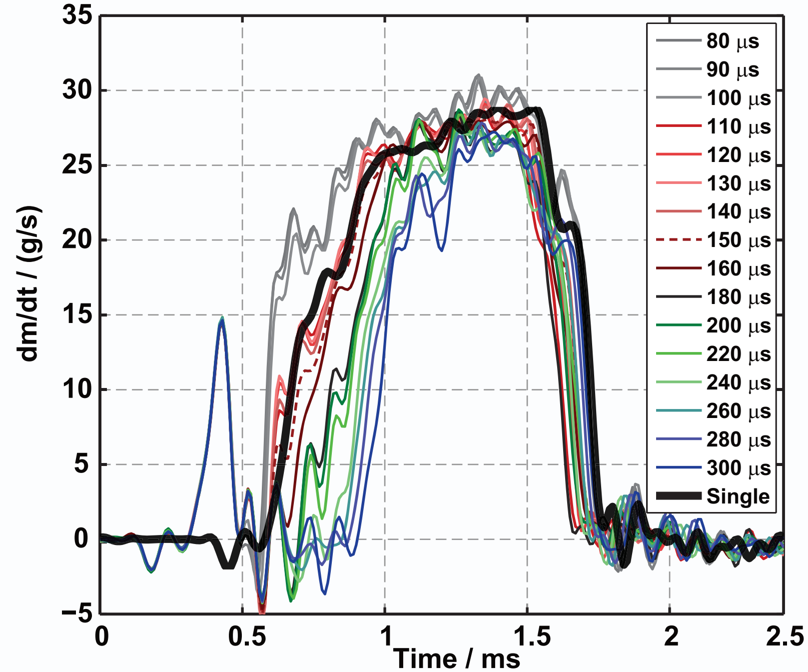
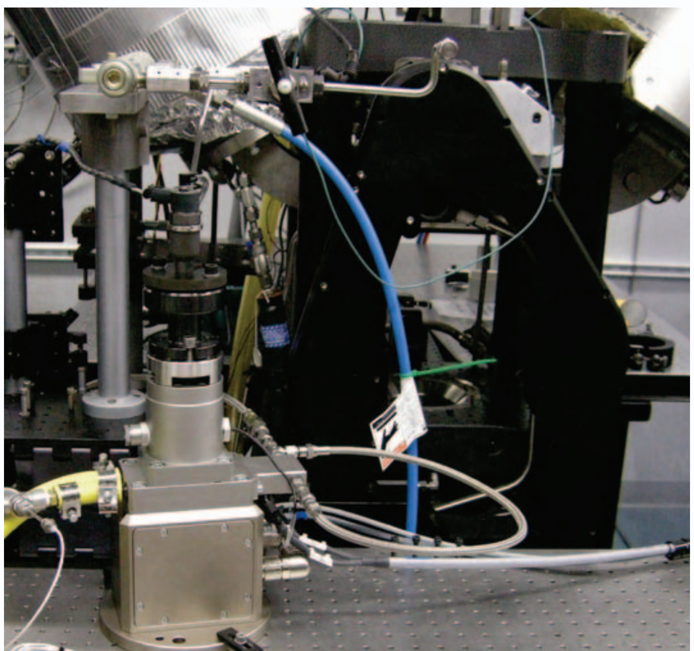


TA: Upgraded FIE and injection rate measurement capabilities

Pre-production Bosch MultiJet II injectors with pressure-balanced solenoids (courtesy GM)

- Allow stable operation with several closely spaced injection events
- Minimum dwell times comparable to piezo-driven injectors (< 100 μs)





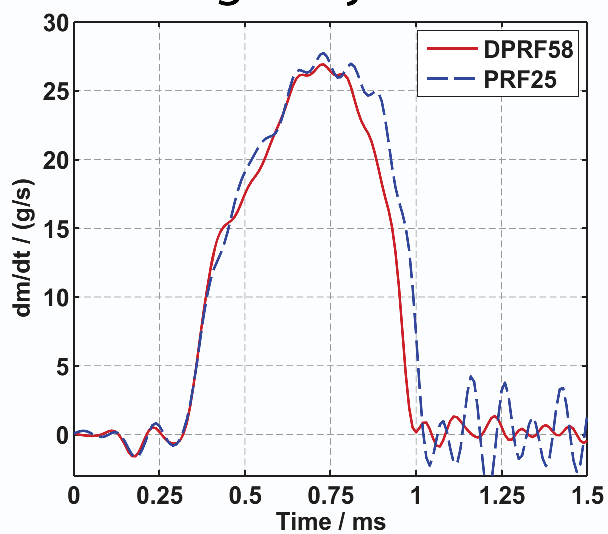
Moehwald **H**ydraulischer **D**ruck**a**nstieg (HDA) provides accurate rate and injected mass

- Can be easily attached to our FIE without changing piping
- Repeatability < 0.075 mg for m < 16 mg
- Backpressure 5 to 95 bar
- Minimum delay between injections 30 μs

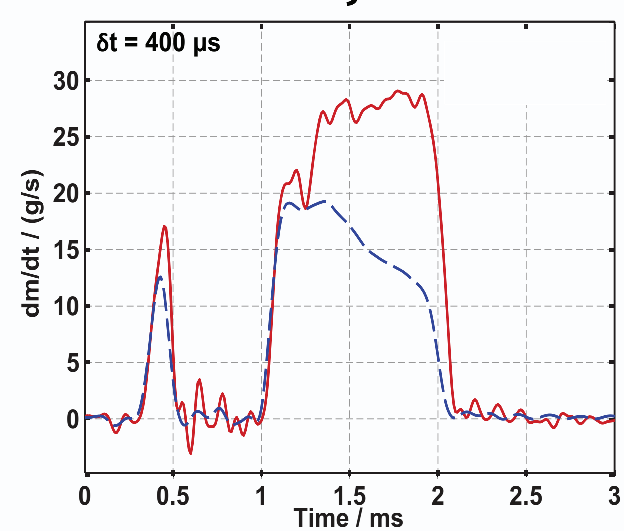
TA: Moehwald HDA measurements

- Provided improved injection rate profiles to modelers (UW, Converge)
- Have characterized the impact of the following variables on injection rate *(submitted to ASME ICEF2014)*:
  - Injector temperature
  - Axial clamping force
  - Energizing current
  - High-pressure line length
  - Injector-to-injector variations
  - Fuel type

Single-injection



Pilot-injection

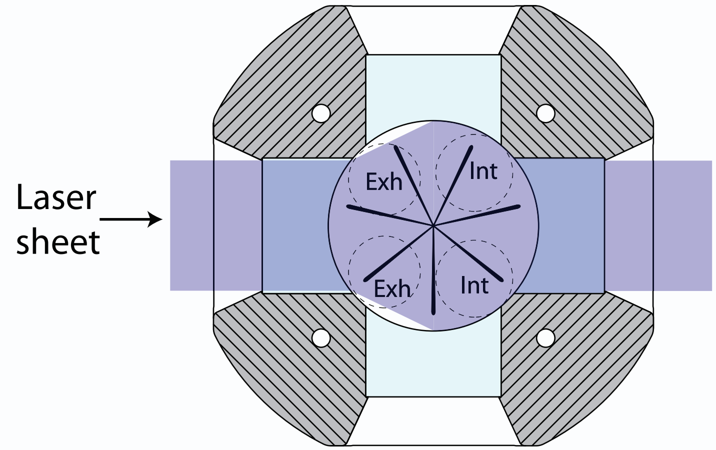


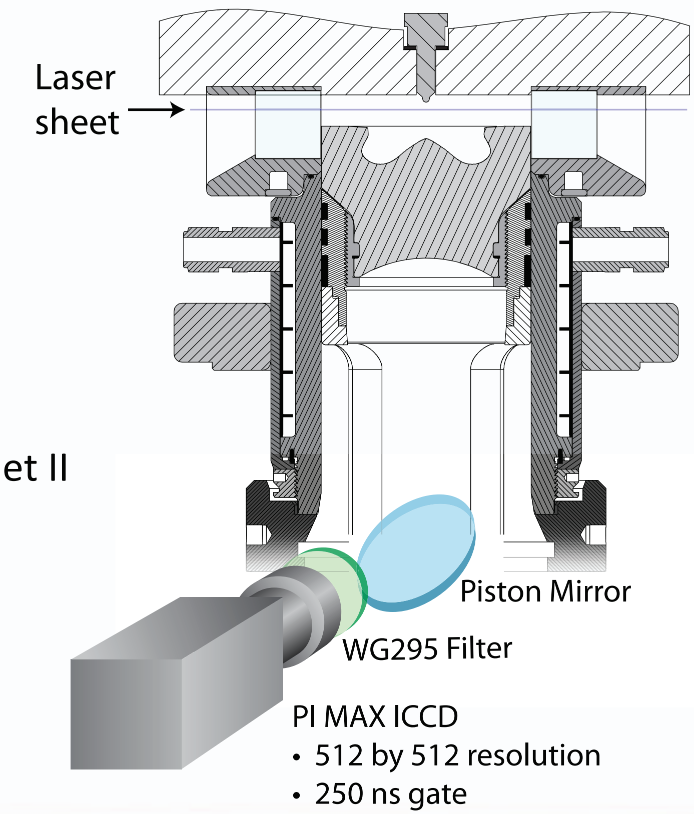
Fuel type has little impact of the shape of a single-injection, but can dramatically affect both the quantity and the rate shape when a pilot is used

Technical Accomplishments (TA): Engine Facility and LIF Set-up

Measurements are made in a GM 1.9L optically accessible engine

- Piston geometry has production-like bowl and valve pockets)
- Top ring-land crevice approximately 3–4 times) volume of production engine crevice)
- Gap-less compression rings reduce blowby)
- Recessed liner windows allow squish volume access @TDC)
- Fluorescence collected through piston)





Engine Geometry

Bore	82.0 mm
Stroke	90.4 mm
Displ. Volume	0.477 L
Geometric CR	16.7
Squish Height	0.88 mm

Injector specifications

Injector	Bosch CRI2.2 / MultiJet II
Nozzle Type	Mini Sac (0.23 mm^3)
Holes	
Nozzle diameter	0.139 mm
Included Angle	149°
Hole geometry	KS1.5/86

TA: Pilot ignition study operating conditions, PLIF measurement locations, & ϕ reporting

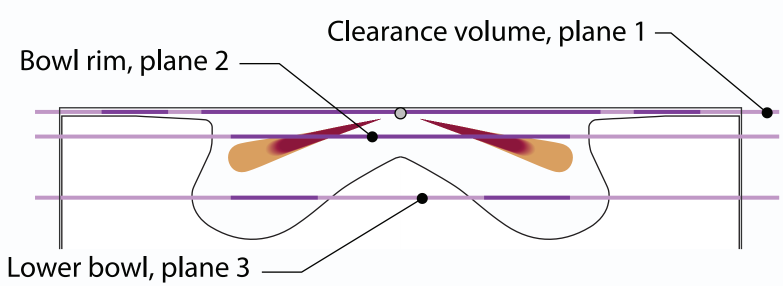
- Pilot ignition characteristics were studied in a matrix of T and [O_2], for sweeps of pilot mass and P_{inj}. SOI and ambient density selected to match OEM engine calibrations at 3 and 6 bar:

$$SOI = -15°;\ \rho_{amb} = 19.6\ kg/m^3$$

$_2$ Concentration – Fired Operation

Intake Temp.	10% O_2	12% O_2	14% O_2	16% O_2	18% O_2
303 K 30°C	813 K 43.8 bar	820 K 44.5 bar	828 K 44.9 bar	833 K 46.1 bar	841 K 46.4 bar
O323 K 50°C	838 K 45.0 bar	845 K 45.4 bar	851 K 46.9 bar	858 K 47.6 bar	866 K 48.6 bar
363 K 90°C	883 K 46.6 bar	890 K 47.2 bar	899 K 47.8 bar	906 K 48.6 bar	915 K 49.3 bar
403 K 130°C	928 K 49.4 bar	936 K 51.0 bar	944 K 50.9 bar	952 K 51.6 bar	961 K 51.7 bar

Avg. near-TDC Cylinder T & P, 15°-TDC



- PLIF measurements were made in three planes & two near-TDC temperatures: 850 & 930 K. Measurements in the upper two planes are reported here

- PLIF measurements are of fuel mole fraction in an inert atmosphere, but can be reported as ϕ for any [O_2]

$$\phi = \frac{\chi_{fuel,d}}{\left(1-\chi_{fuel,d}\right)} \cdot \frac{24.5}{\chi_{O_2}}$$

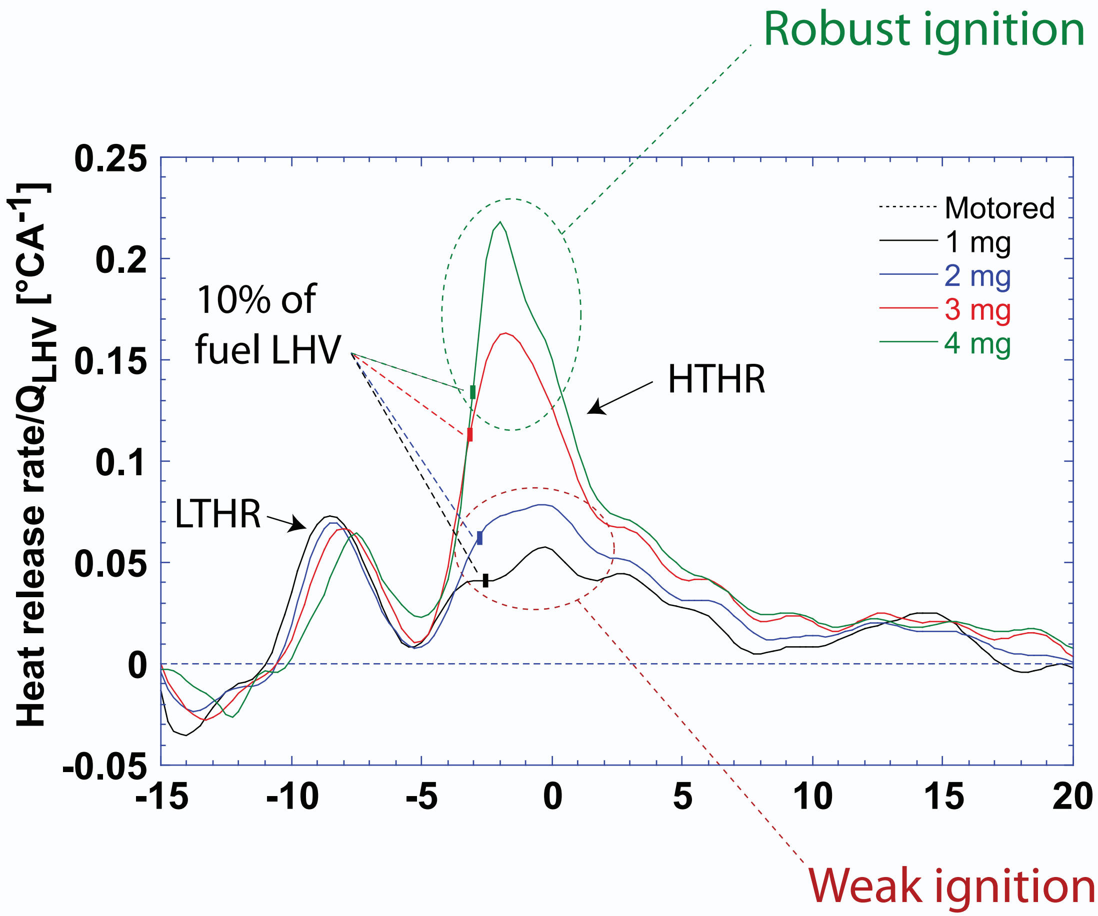
TA: Definitions of ‘robust’ ignition & ignition delay

- A robust ignition event is determined by the HTHR portion of the heat release curve

  (LTHR, normalized by fuel mass, is an insensitive measure)

  Robust ignition occurs when 40% of the injected fuel’s LHV is released between SOI and 10° aTDC

- **Ignition delay is defined as the time from SOI until 10% of the fuel LHV is released**



For robust ignition events, this consistently corresponds to the rising flank of the heat release curve, near the maximum $d\dot{Q}/dt$

(definitions based on maximum $d\dot{Q}/dt$ were inconsistent at low $\dot{Q}$)

TA: The minimum temperature required for robust ignition varies with $[O_2]$, mass, & P_{inj}

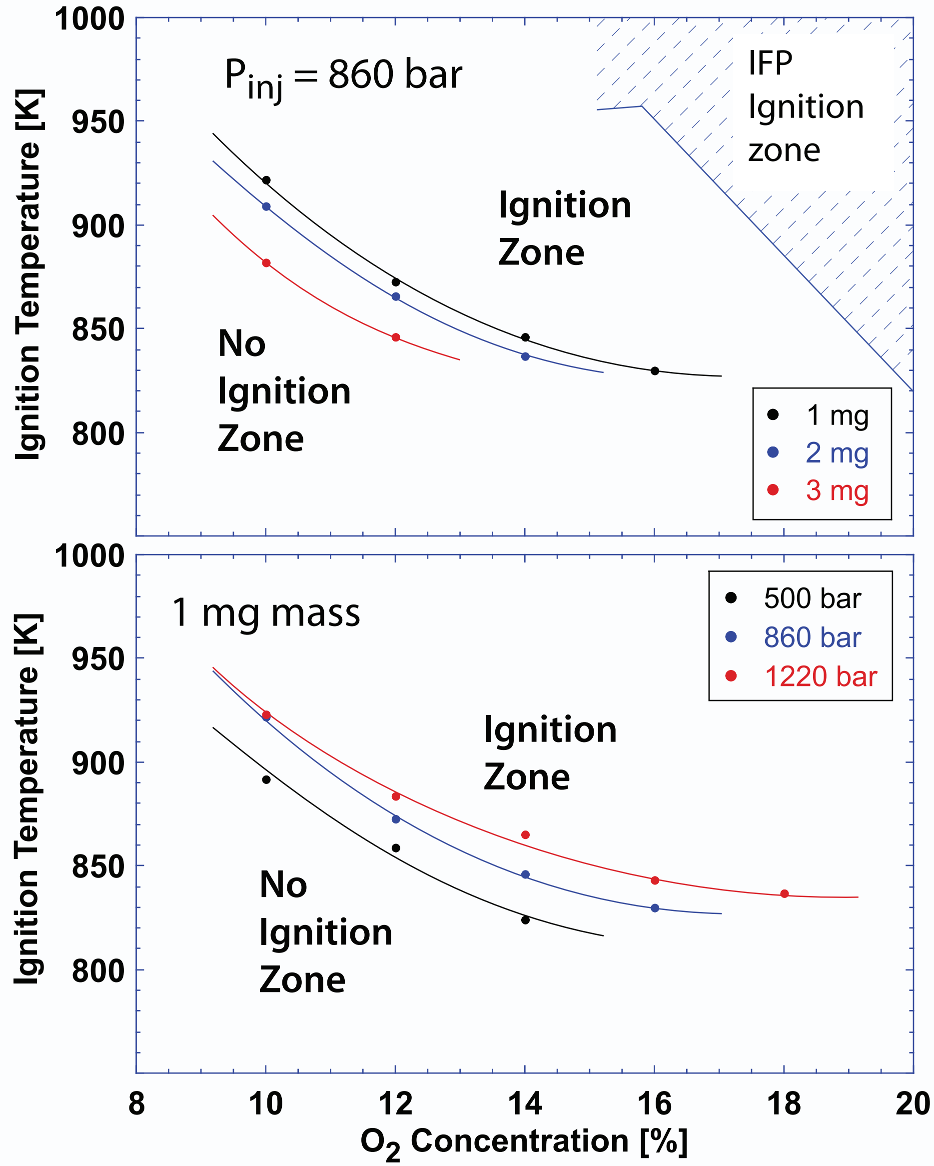
- Higher temperatures and $[O_2]$ promote ignition

  The discrepancy with other measurements reported in the literature cannot be explained by definition of ignition, temperature computation, fuel CN, charge composition)

- Higher mass and lower injection pressures also promote ignition

Recalling our mixture formation measurements –

Richer mixtures appear to promote ignition



TA: The impact of temperature & [O_2] on ignition delay provides additional information

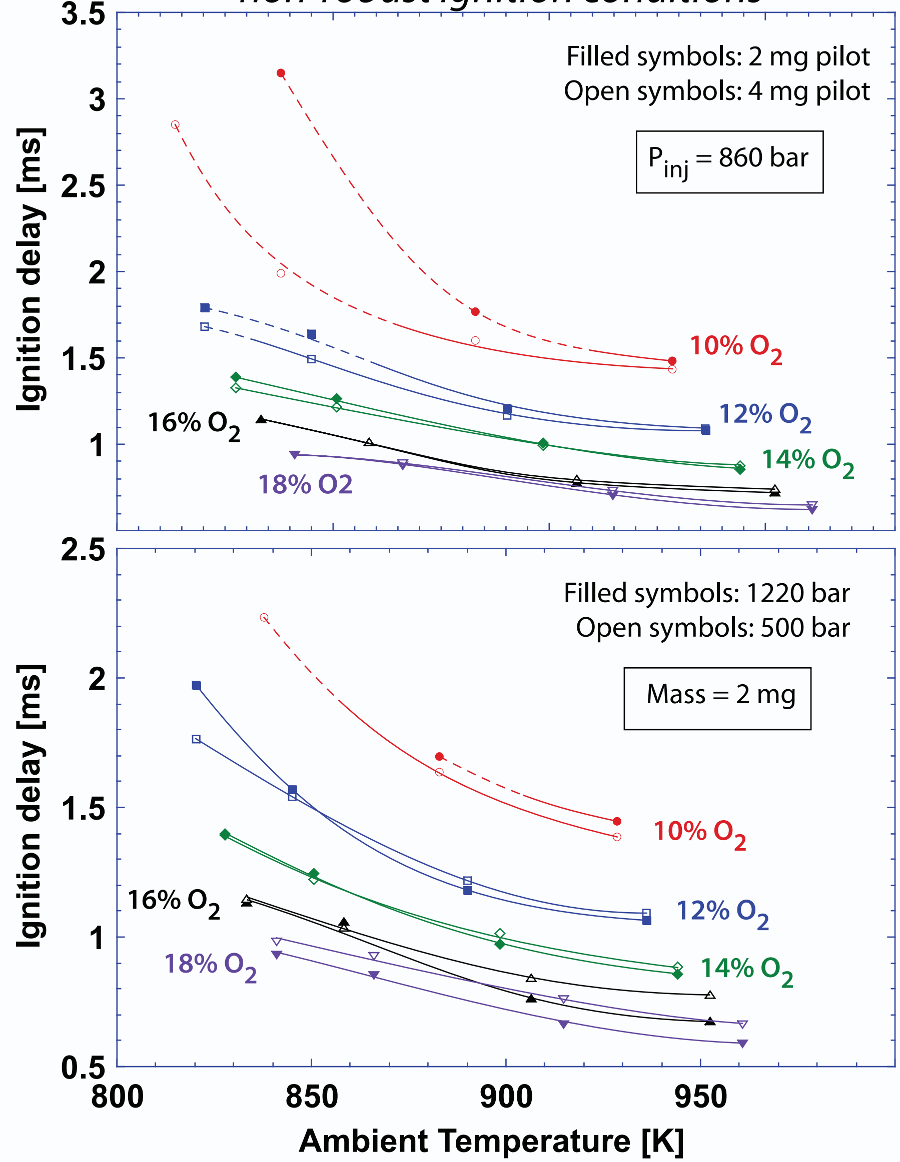
- Higher temperatures and [O_2] again promote ignition
- At low temperatures and [O_2], higher mass and lower injection pressures (*richer mixtures*) promote ignition

$$\tau = A\phi^{\alpha} P^{\beta} \chi_{O_2}^{\delta} \exp\left({E_a}/{RT} \right)$$

(α & δ are negative constants)

- At high temperatures and [O_2], lower mass and higher injection pressures (*leaner mixtures*) promote ignition

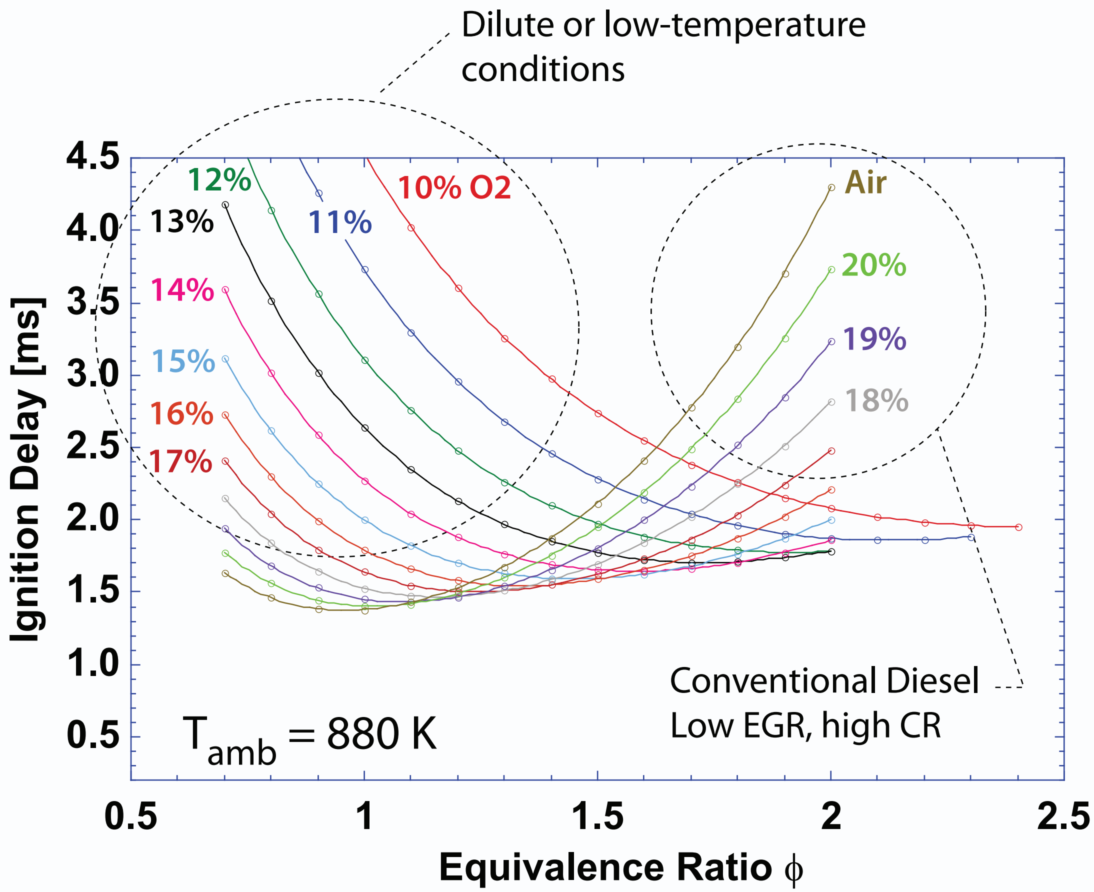
Dashed lines indicate non-robust ignition conditions



TA: Simulations with detailed kinetics show an optimal ϕ that mimimizes ignition delay

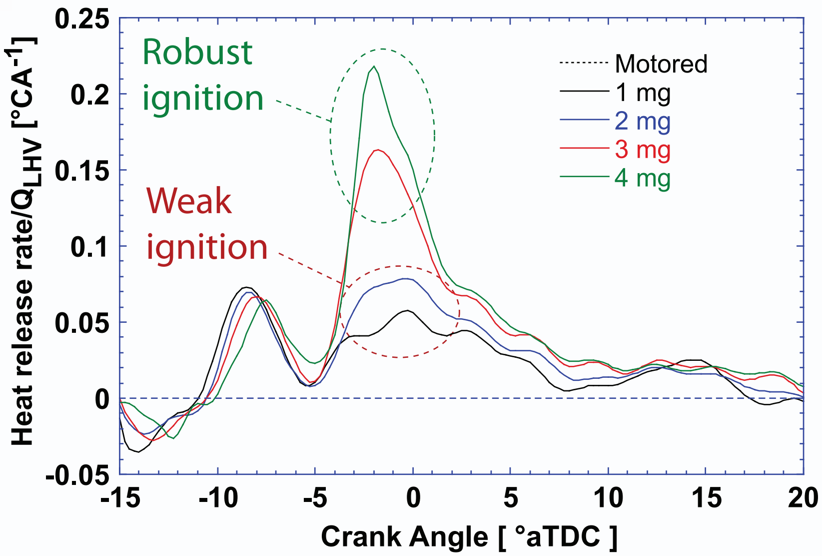
- Under dilute, lean (or low temperature) conditions, over-mixing can lead to longer ignition delays
- Under low dilution, rich conventional conditions under-mixing will typically extend the ignition delay
- The minimum ignition delays predicted are considerably larger than those measured

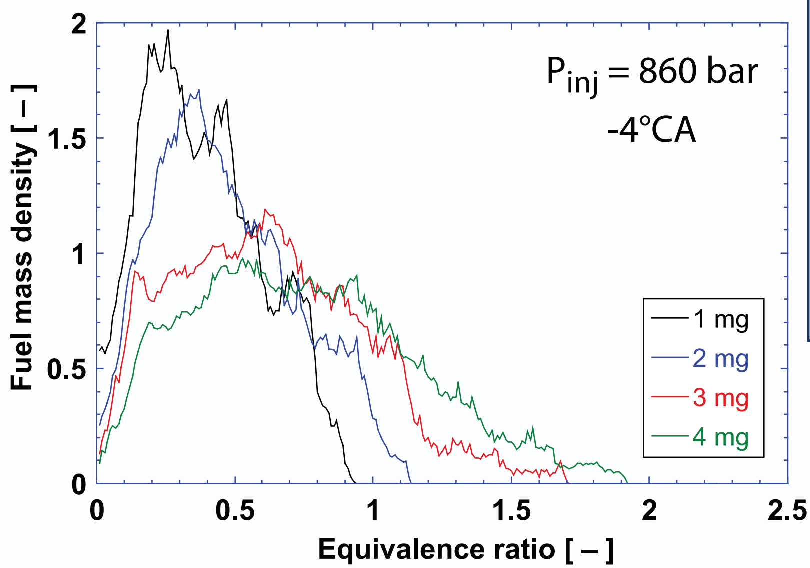
  (cf. ~ 0.8 ms @ 18% O2 and avg. near-TDC temperature ~ 880 K)

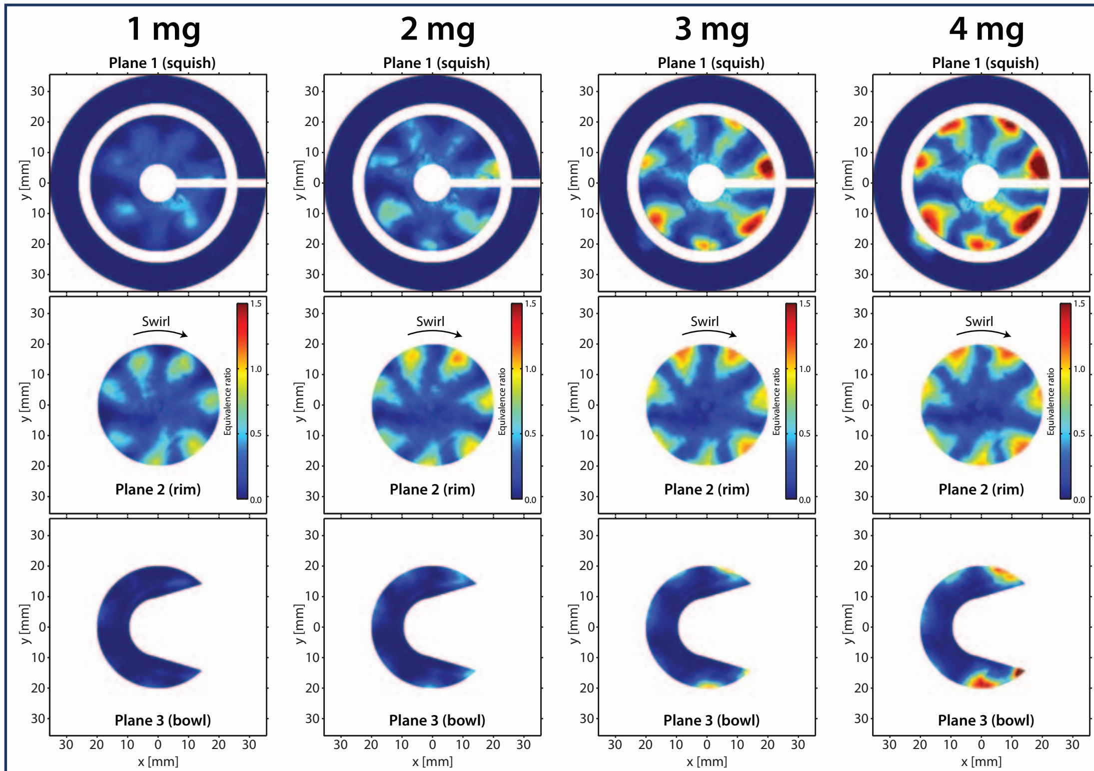


- For $0.14 < [O_2] < 0.20$, the optimal ϕ to promote ignition is between ~ 1.0 and 1.6
- Physically, there is an optimum entrained mass per unit mass fuel. Too little mass delays LTHR; too much mass reduces LTHR temperature rise and delays HTHR

TA: PLIF measurements confirm linkage between ϕ distributions & ignition as pilot mass varies



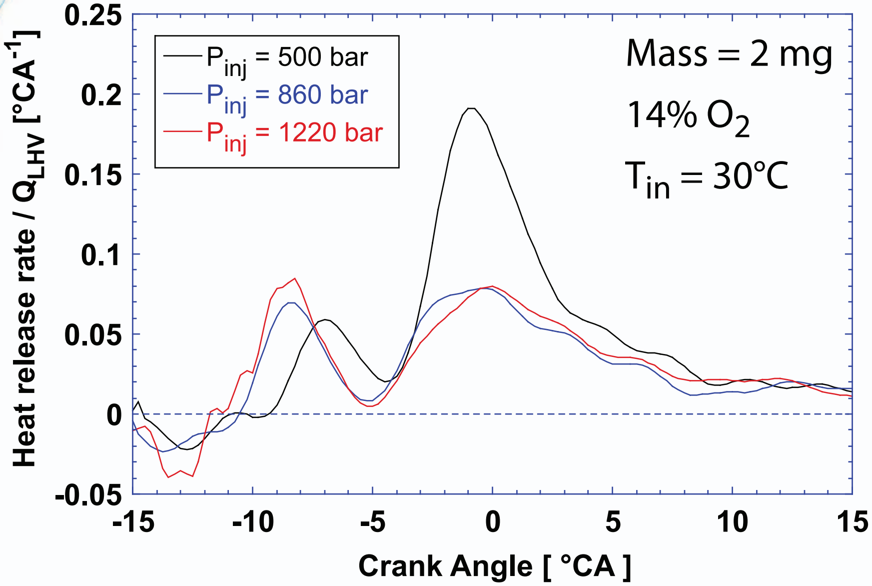




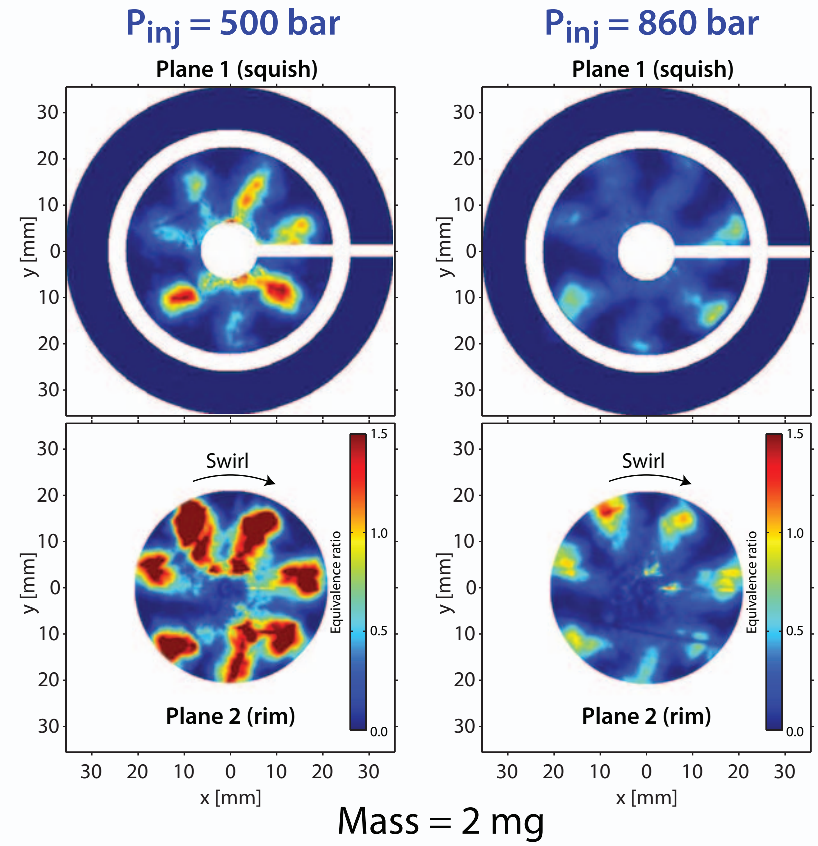
ϕ-distributions at the time of ignition, -4° aTDC

- Richer mixtures are formed with increased pilot mass
- Robust ignition is seen when a significant amount of mixture is in a favorable range (ϕ > 1)

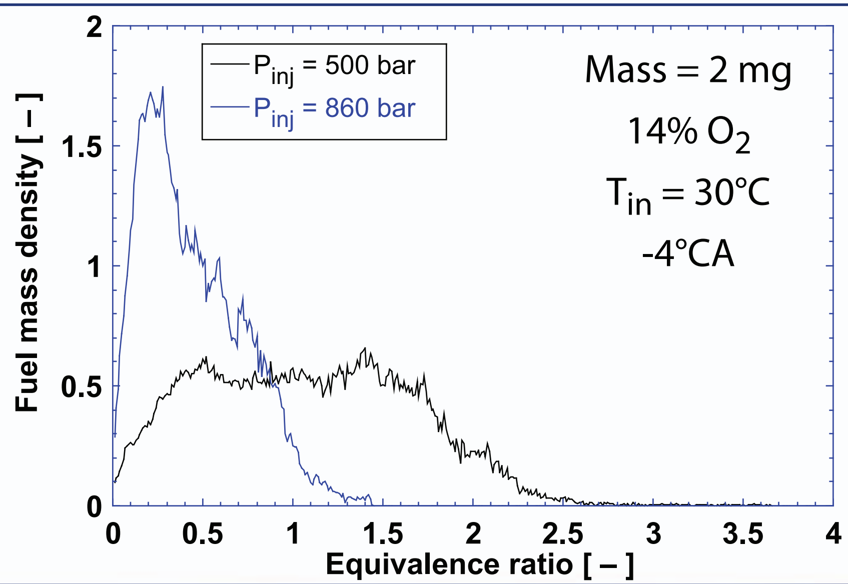
TA: The impact of injection pressure on ϕ-distributions and ignition is also confirmed



- Low P_{inj} promotes robust ignition



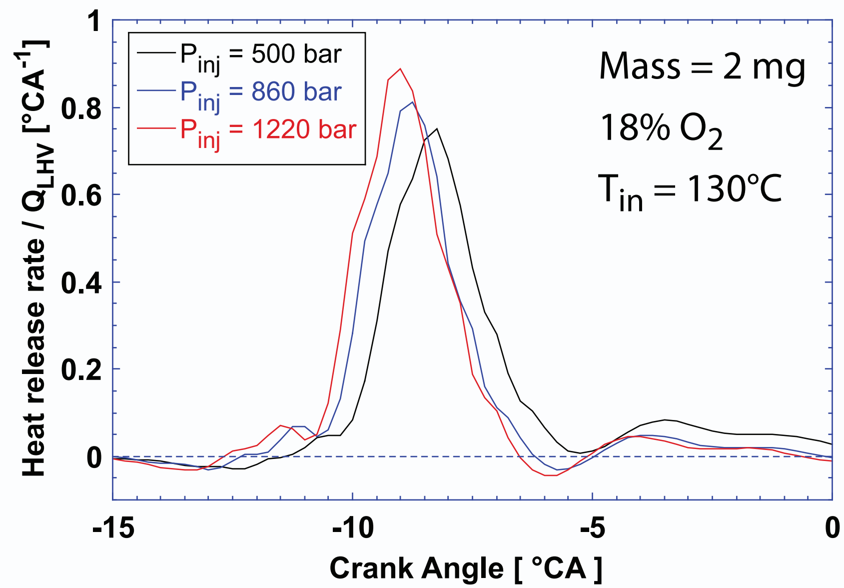
- Low P_{inj} results in richer mixtures and lower penetration



- Fuel mass distributions are much more favorable for ignition at low P_{inj}

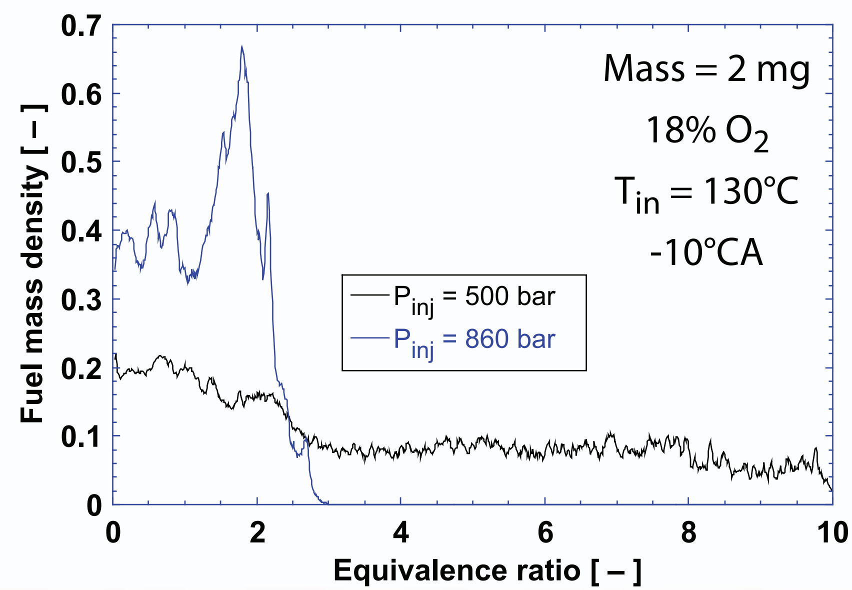
TA: Under conventional diesel conditions the ϕ–ignition behavior is also consistent

- There is an unambiguous decrease in ignition delay as injection pressure is increased under high-temperature, low-dilution conditions



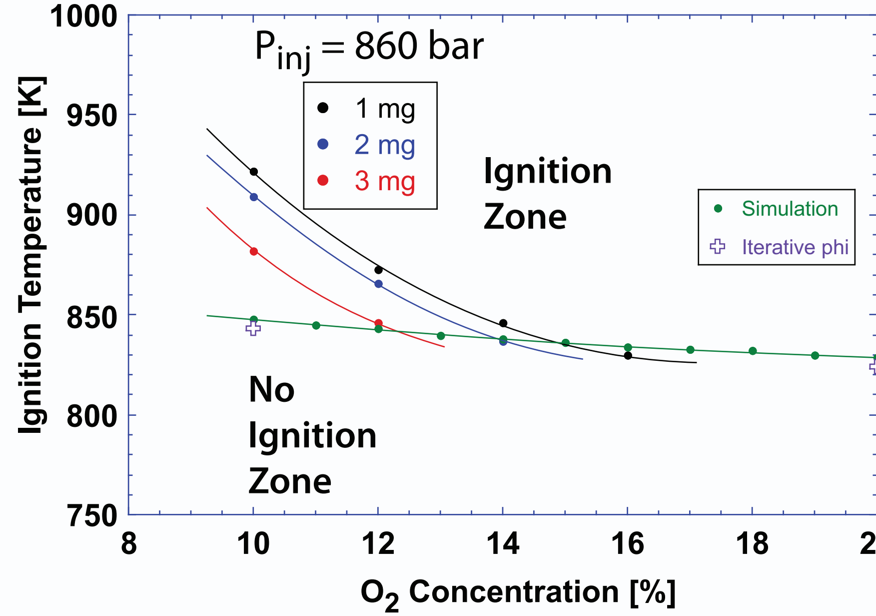
- A far greater fraction of the fuel is found in mixture with equivalence ratios that promote ignition ($\phi < 2$) when the injection pressure is high

  In this case, a reduced physical component of the ignition delay may also contribute.



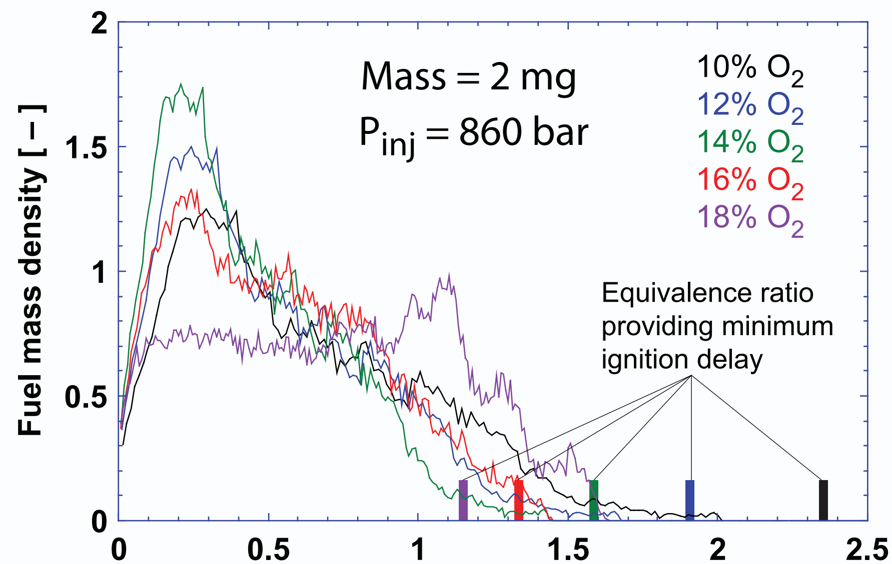
TA: ϕ-distributions also explain why ignition temperatures are higher than predicted

- Minimum ignition temperatures are under-predicted at lower O_2 levels (higher dilution)



- At lower O_2 levels, over-lean mixture is formed...

  ...there is little or no mixture at the ϕ providing optimal ignition behavior!



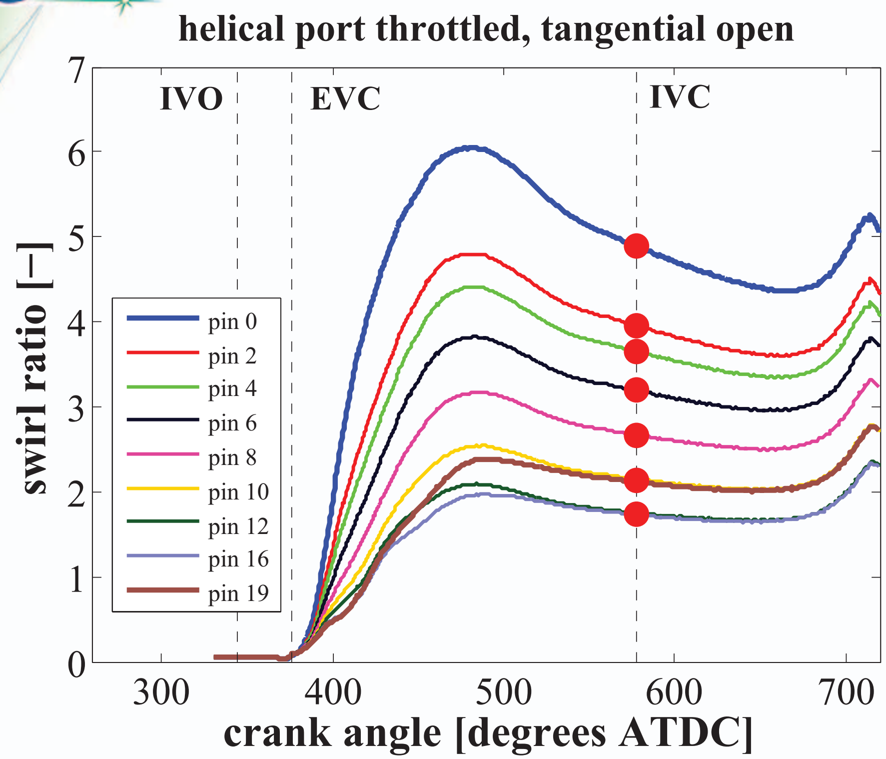
TA: Comparison with multi-dimensional modeling

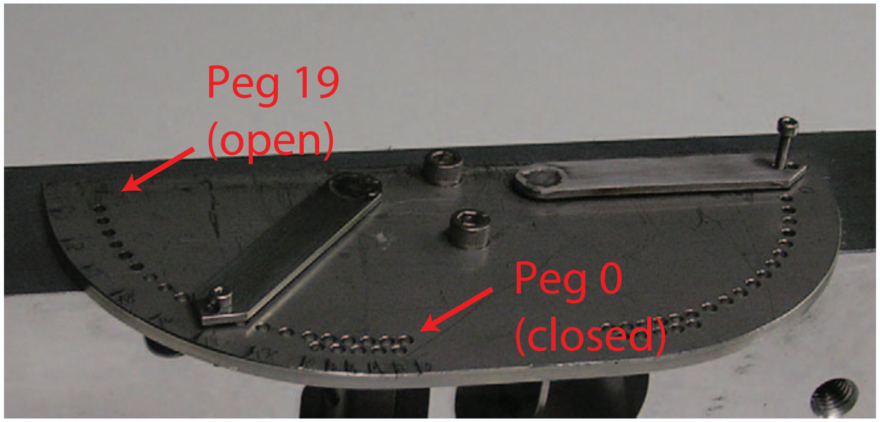
- Status April 2013: Main shortcomings were under-prediction of turbulent diffusion and jet deflection/penetration overly sensitive to swirl. **Actions:** check accuracy of mean swirl predictions; implement 360° mesh and examine flow differences

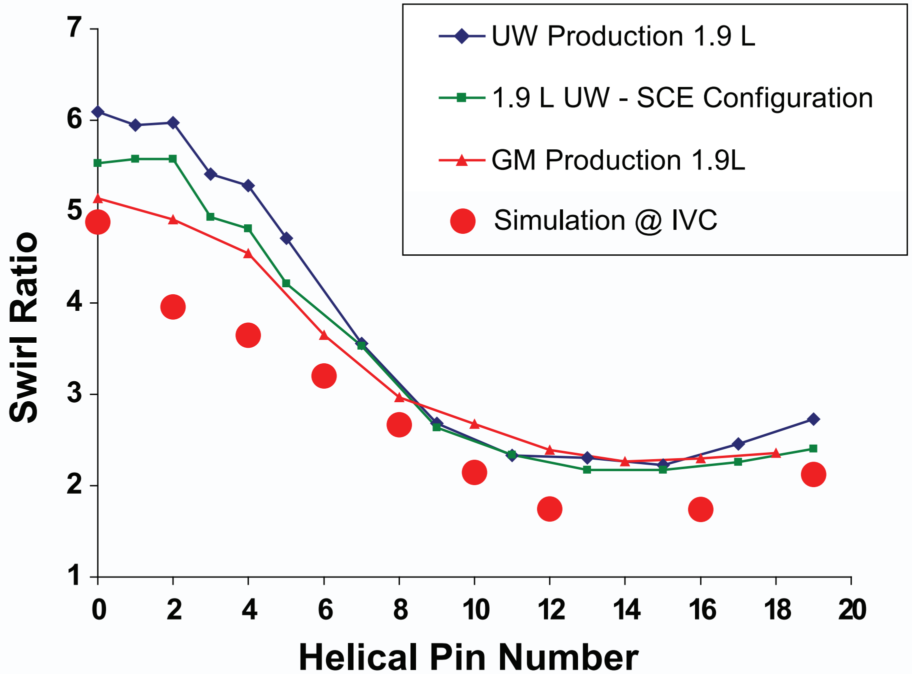
Progress last 12 Months:

- **Flow and injection modeling**
  - Improved 360° mesh generated; better spray/combustion numerics supporting large-scale computations, parellelization of flow/spray solution in progress. Results show significant jet-jet variations - see extra slides
  - Cell deactivation method implemented for modeling inlet throttles
  - Predicted near-TDC swirl levels compared with GM/UW flowbench results
  - Improved inlet (port) manifold temperature and temporally resolved pressure supplied; in-cylinder motored temperature measurements in progress
  - Injection rate measurements with Moehwald HDA
  - Full induction stroke velocity field measurements in progress
- **Pilot injection ignition studies**
  - Examined underlying assumptions involved in modeling diesel fuels with heavy fuel physical properties and chemical mechanisms associated with PRF mixtures
  - Established current capabilities of modeling minimum ignition temperature

TA: Predicted vs. Measured Swirl Ratios







- Trend reproduction is excellent
- Simulated in-cylinder swirl ratios are slightly lower than those measured

Suggests that over-prediction of in-cylinder swirl ratio is not the primary cause of over-predicted jet deflections

Need to look to the entrainment modeling

TA: Assessment of the use of gasoline PRF mixtures in both modeling and experiments

Reduced kinetic mechanism for DPRFs not available (full mechanism not validated!)

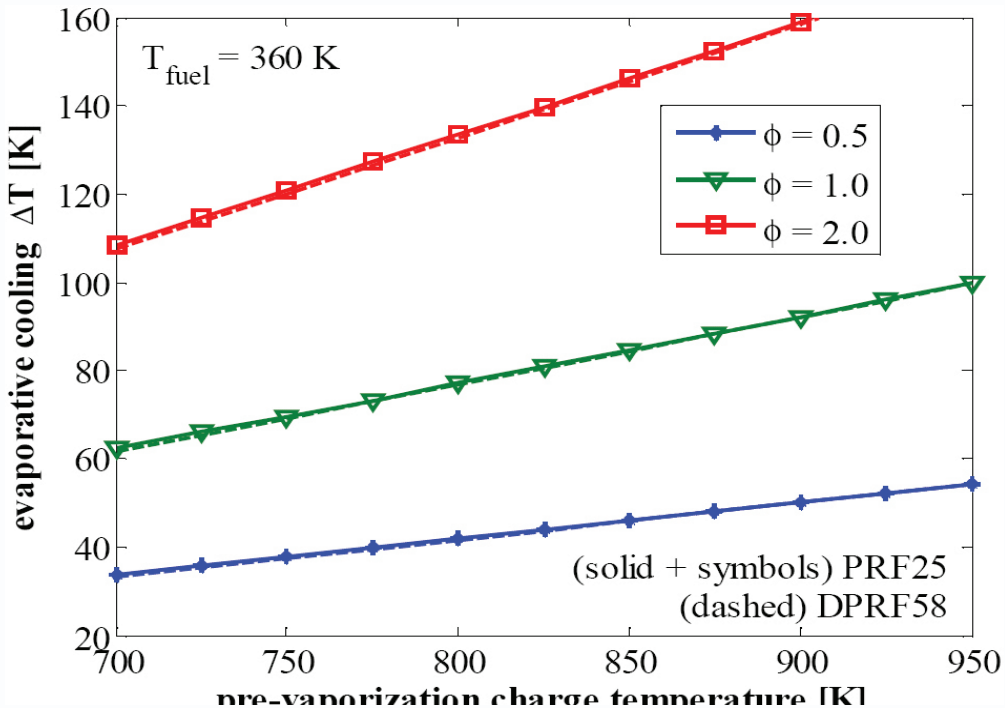
- Use physical properties of DPRFs (or dodecane) for spray/mixture prep. modeling
- Use well-validated kinetics and reduced mechanisms of the lighter gasoline PRFs

Equal ignition delays were obtained in the engine for DPRF58 mixtures and PRF25 mixtures. Can we use PRF25 kinetics to model the ignition process of a DPRF58 mixture?

Are the local mixture temperatures after vaporization and adiabatic mixing the same for DPRF58 mixtures and PRF25 mixtures?

That is, are the initial temperatures we supply to the chemistry models appropriate?

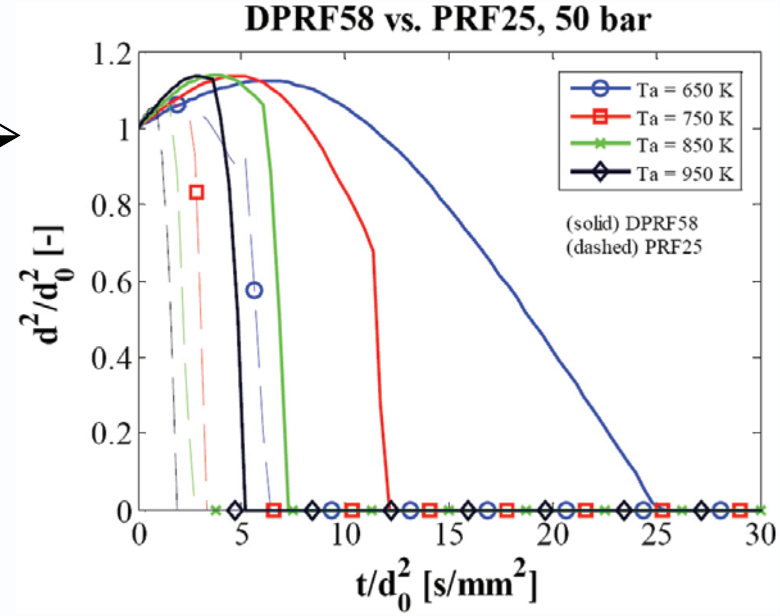
Yes... provided the final ϕ is the same (result generalizes to other PRF/DPRF blends)

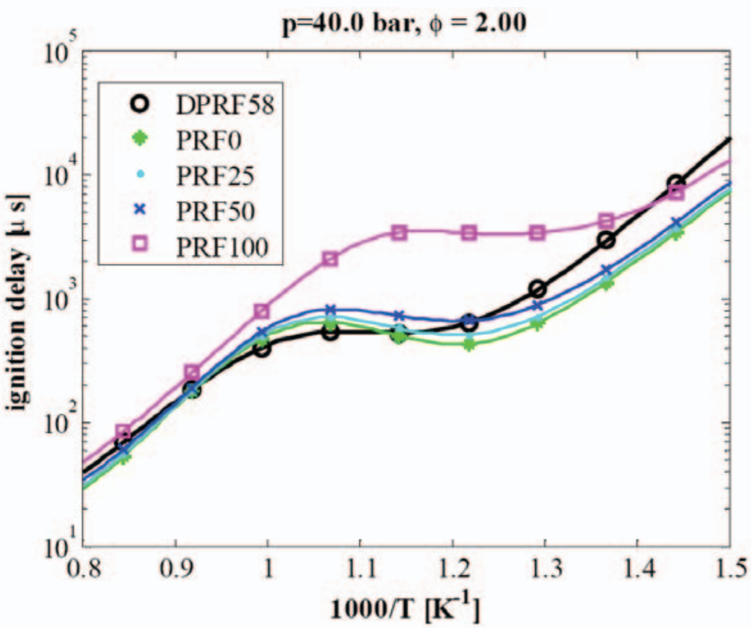


TA: DPRF/PRF vaporization times and ignition delays can differ significantly

- Comparisons of droplet vaporization times as well as liquid lengths indicate more rapid mixture formation for PRF mixtures

  (Our previous HC/CO work showed more over-lean mixture was formed with lighter fuels)

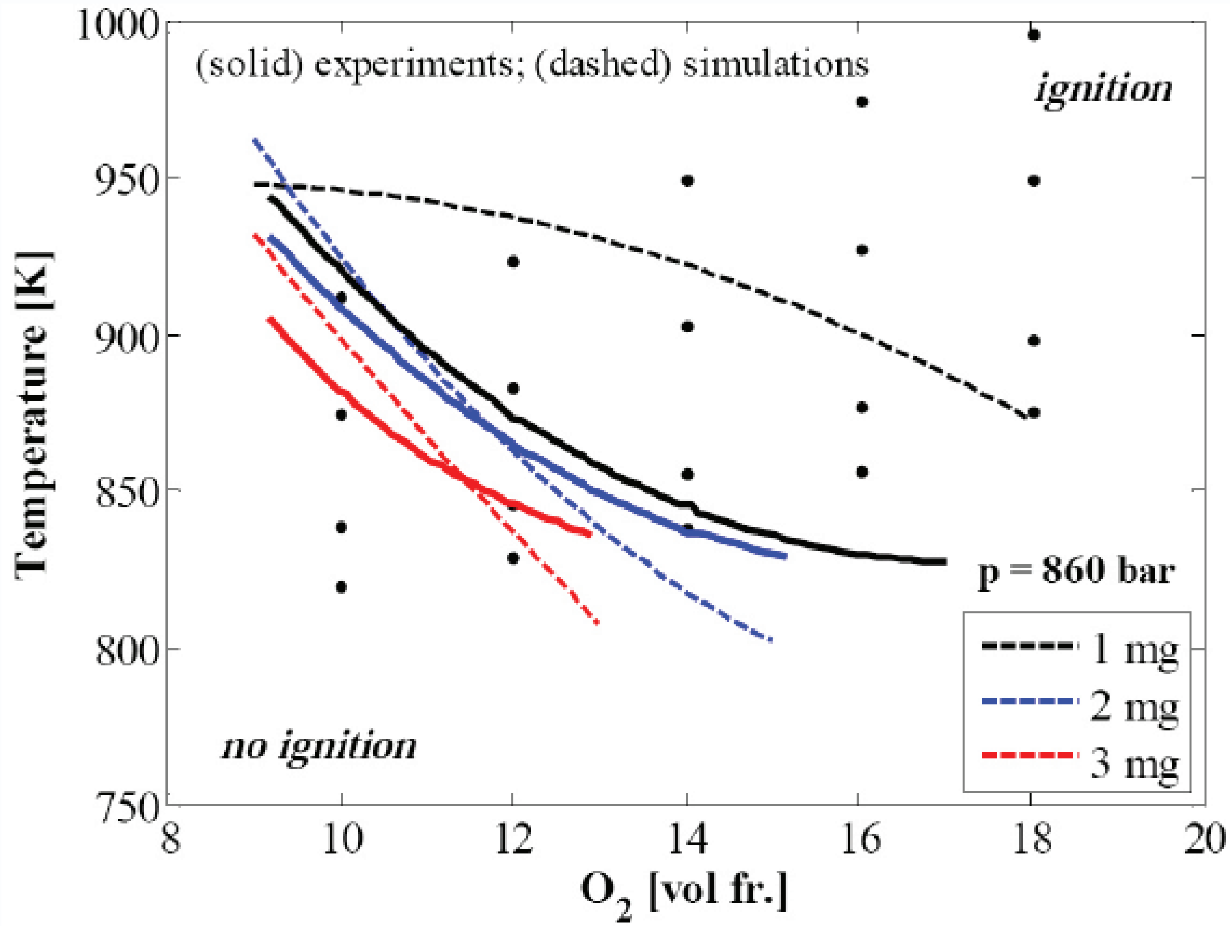




- PRF mixtures can over-predict or under-predict DPRF ignition delays, depending on T * ϕ
- Current practice may lead to erroneous results due not only to mixture formation issues, but also to chemistry modeling
- Matching ignition delays experimentally likely involves a balancing of mismatched mixture preparation times and ignition delays

Using fuels with realistic properties is important for both the experiments and models

TA: Nevertheless, predictions of pilot ignitability are reasonable



- Reasonable agreement in the minimum temperature required for ignition is found for larger pilot quantities (richer mixtures)

  In light of the under-prediction of turbulent diffusion in the equivalence ratio fields, this suggests lean mixture kinetics is the primary cause of the discrepancy

Response to Reviewer's Comments

- The large crevice volume of the optical engine is a concern with regard to HC/CO – additional modeling work might be helpful. Also, is there a need for metal engine experiments?

  Response: Previous work has shown that the optical engine HC/CO emissions closely match metal engine emissions until injection is very advanced, when crevice HC become important. We are actively working to reinstate collaborations with a UW group that has the same geometry metal engine. Previous modeling work has helped clarify the impact of the crevice on in-cylinder flows – see AMR 2009

- The effect of reverse squish flow needs to be investigated and correlated with CO & HC emissions

  Response: We are working actively to obtain both velocity and fuel measurements in the squish zone. To date, the velocity measurements have been unsuccessful, but we are continuing the effort

- Focus on interaction with the modeling effort to identify the source of the discrepancies

  Response: This year we focused on a number of issues: full induction stroke velocity measurements, use of DPRF fuel and appropriate modeling of properties and kinetics, providing accurate injection rate profiles

- Need to consider injector protrusion/targeting, injection pressure, and operating strategy along with the Ford bowl geometry

  Response: Targeting information and appropriate injection strategies will be provided by Ford

- Evaluate additional diagnostics to fully characterize the injector to help with model validation

  Response: We have acquired and set-up a Moehwald injection rate analyzer to provide accurate rate profiles and assist in defining conditions for multiple injection strategies

- There should be more emphasis on cold-start conditions which are crucial to Tier 2, Bin 2 goals

  Response: This is planned for future work; fast-acting, multijet-II injector should help

Collaborations

Within Vehicle Technologies program:

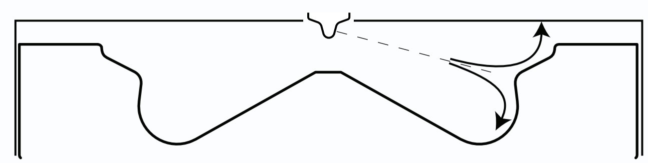
- Formal collaboration between SNL-UW
- Data transfer to OEMs (Cat new this year, NDA's (Ford/GM) to allow transfer of geometry
- New collaboration with Convergent Science
- Participation in Advanced Engine Combustion group, including presentations and discussion with 21 industrial/national laboratory partners:

Ex-Vehicle Technologies program:

- Separate GM funding, very close collaboration
- Strong ties with Lund University, Friedrich-Alexander University, Université de Poitiers
  - Exchange students perform research at Sandia
  - Fund. diag. devel. at Universities, application at Sandia
  - Joint review articles on engine flows and combustion
  - SNL staff participates in LU research projects

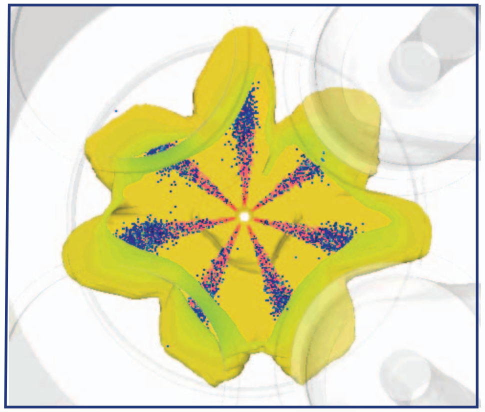
Future Work

- Complete full induction stroke flow measurements and comparison with model predictions (UW and Convergent Science)
- Investigate mixture formation with close-coupled multiple-injection strategies
  - Close-coupled pilots (large impact on combustion noise)
  - Multiple, short, close-coupled injections at light load and cold start conditions to limit penetration and over-mixing
  - Explore impact of swirl on reducing over-mixing at light load
- Investigate piston geometry effects
  - Impact on near-TDC flow structure
  - Mixture formation processes for both LTC and conventional diesel conditions



Ford stepped-lip bowl

- Continue to enhance large-scale computation capability (UW)
- Assess causes of jet-to-jet variations in fuel penetration and mixing (UW)
- Examine and improve near-nozzle sub-models impacting jet entrainment, penetration, & deflection (UW)



Summary

Relevance

- Project addresses lack of fundamental knowledge and lack of modeling capability
- Supports LTC combustion regimes, conventional diesel regimes, and NG ignition

Approach

- Approach balances experiment with zero- & multi-dimensional simulation; links strongly to industrial partners

Technical Accomplishments

- Significant upgrades to FIE and injection rate measurement capabilities, supporting both experiments and modeling
- Pilot ignition study clarified effect of T, O_2, mass, and P_{inj} on ignitability; identified optimal ϕ for ignition, and resolved contradictory (rich/lean) parameter effects
- Major improvements to computational efficiency to support large-scale computing
- Identified shortcomings of current modeling & experimental approaches; established reasonable predictive capability for pilot ignition

Collaborations

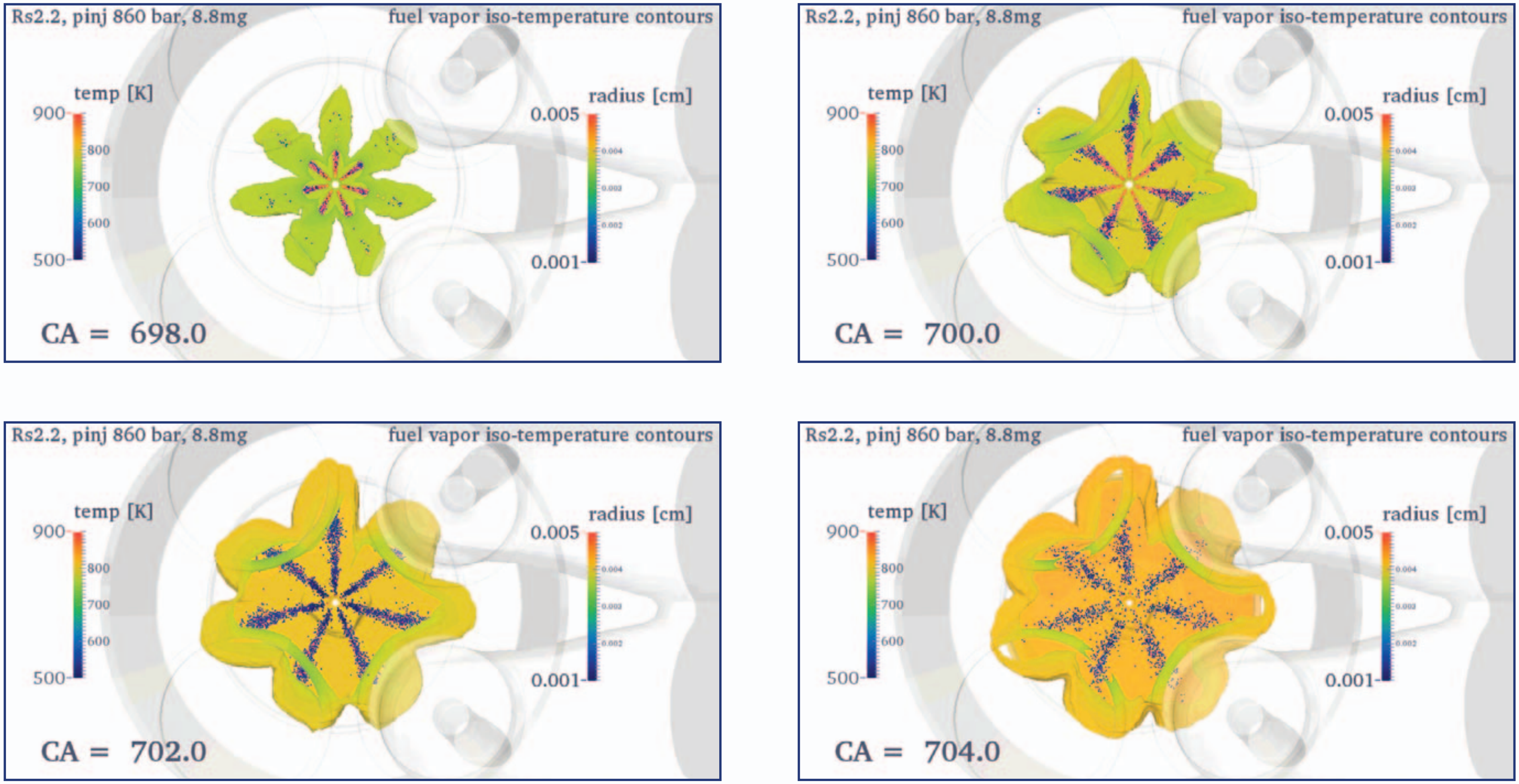
- Multiple collaborations with OEMs, universities, code vendors; MOU participation

Future Work

- Will continue mixture preparation studies with new bowl geometries and close-coupled multiple injections
- Continue with model development and validation efforts related to both flow and combustion prediction

Technical Backup Slides

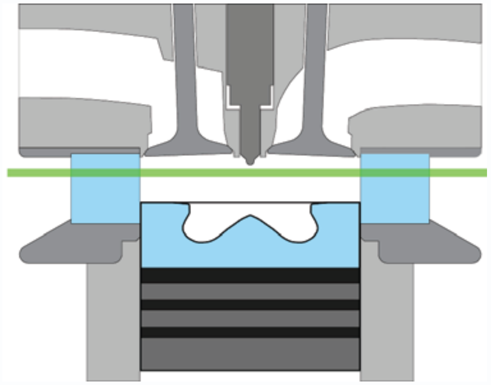
TA: First results of fuel-distribution using 360° grid show significant jet-jet variations

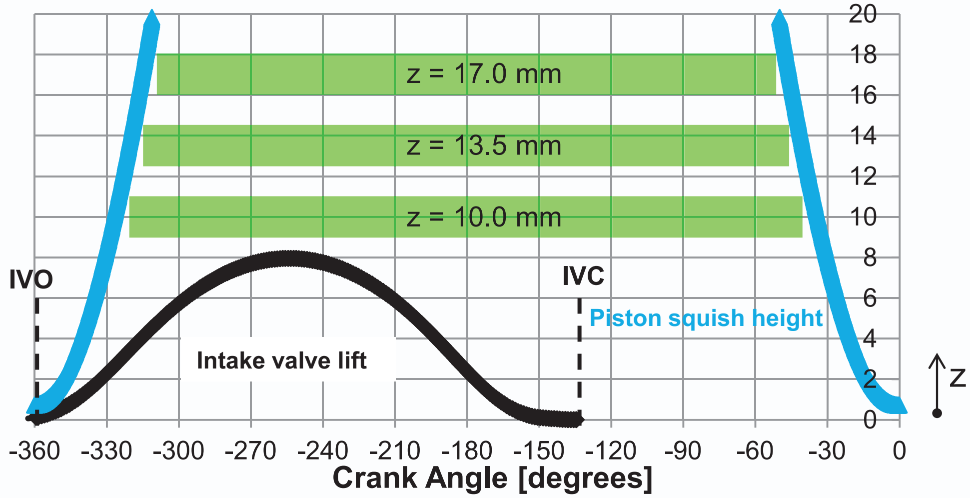


- Initial analysis suggests penetration is correlated with local squish flow strength

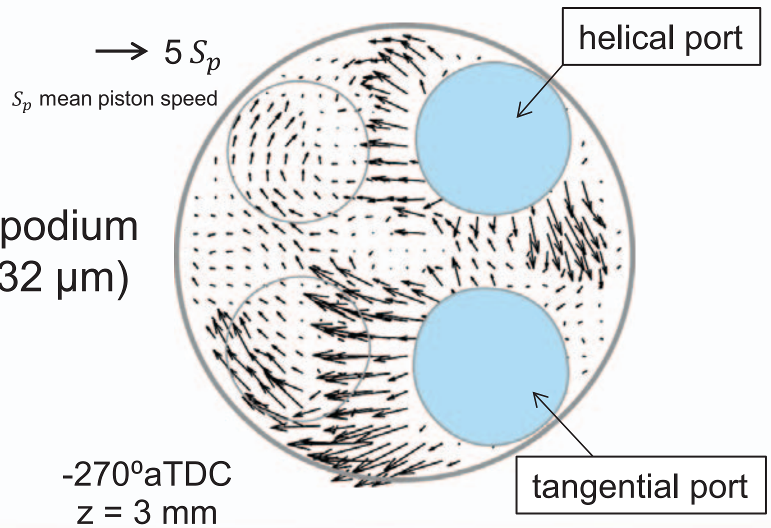
TA: Significant progress has been made in mapping the flow during induction

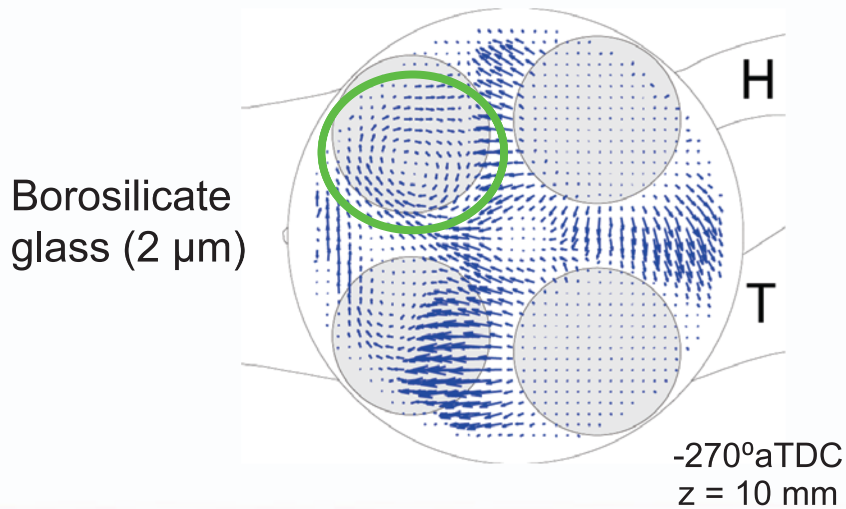
- Measurements have been made at R_S=1.5, 2.2, and 3.5. Measurement planes and crank angles are selected to avoid interference by the intake valves and the piston:





- Larger seed particles provide higher S/N, but do not closely follow the flow:

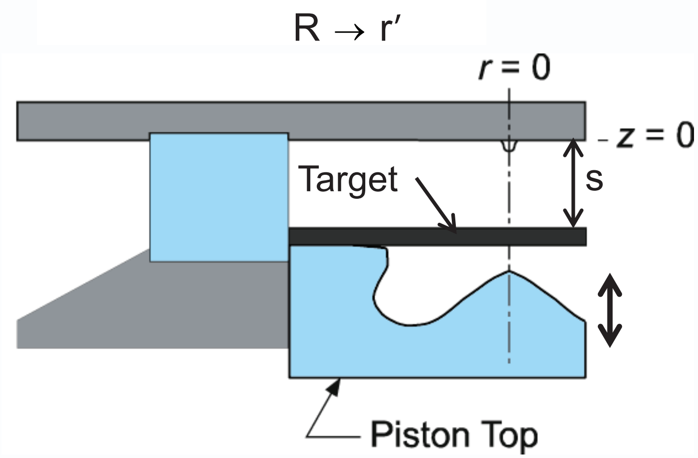




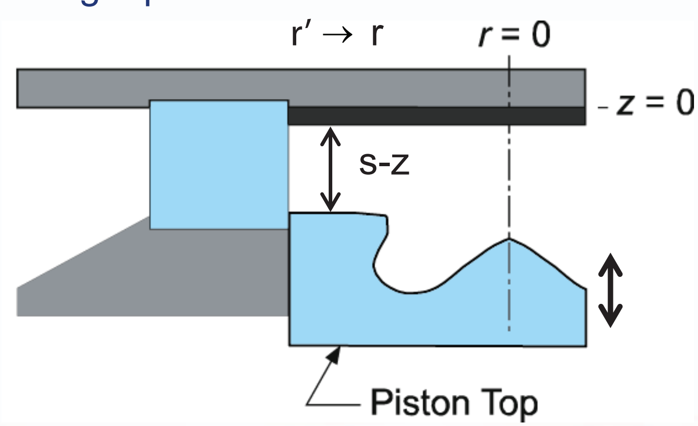
TA: Apparent PIV particle displacement is due to both flow & changing image distortion

- An analytical representation of distortion is needed to separate the two causes of apparent particle motion

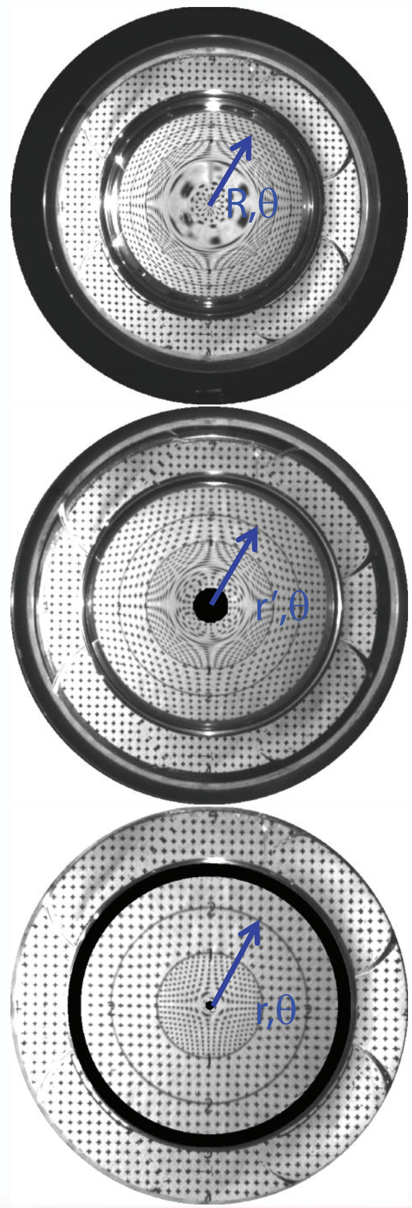
Step One: Map radius R in raw target image to radius r′ in the piston top plane



Step One: Map piston top radius r′ to target plane radius r



Raw Target Image



Physical Space (Final result)

Mapping R→r′ accounts for changes in magnification and distortion with changes in piston position:

$$r' = r_0' + k_1(s - s_0)$$

$$k_1 = aR^3 + bR^2 + cR + d$$

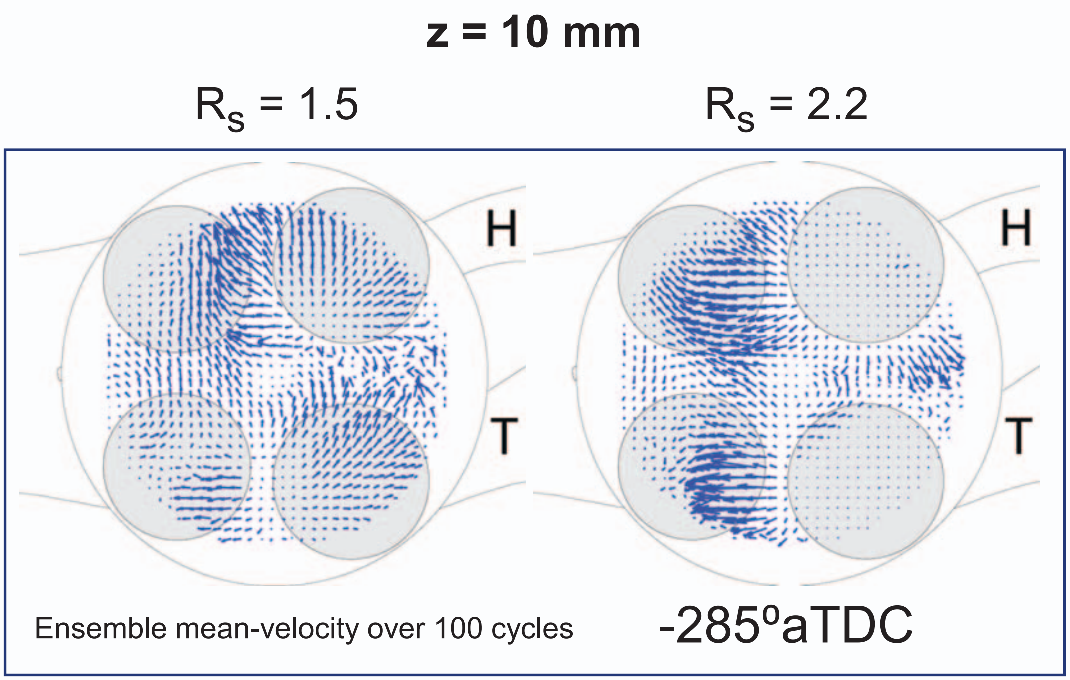
Mapping r′→r accounts for changes in distortion with distance of the target from the piston (s-z):

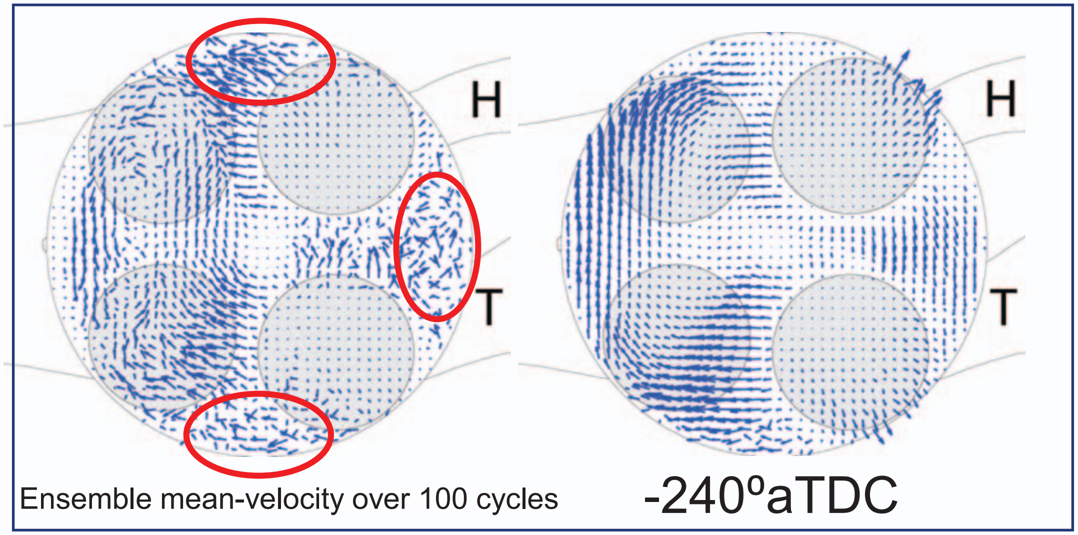
$$r = R_0 + k_2(r' - R_0')$$

$$k_2 = \alpha(s - z)^2 + \beta(s - z) + \gamma$$

TA: Details of flow structures in intake are strongly dependent on swirl ratio

- S/N is adequate when the piston is close to the measurement plane
- But they deteriorate as the piston approaches BDC





We are currently endeavoring to improve the S/N and plan to repeat the measurements