Spray Combustion Cross-Cut Engine Research

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Sandia National Laboratories

FY 2011 DOE Vehicle Technologies Program Annual Merit Review
Project ACE005, Salon E, 10:00 – 10:30 AM, Tuesday, May 10, 2011

Sponsor: **DOE Office of Vehicle Technologies**
Program Manager: **Gurpreet Singh**

Overview

Timeline

- Project provides fundamental research that supports DOE/ industry advanced engine development projects.
- Project directions and continuation are evaluated annually.

Budget

- Project funded by DOE/VT:
  FY10- $660K
  FY11 - $730K

Barriers

- Engine efficiency and emissions
- Load limitations for LTC
- CFD model improvement for engine design/optimization

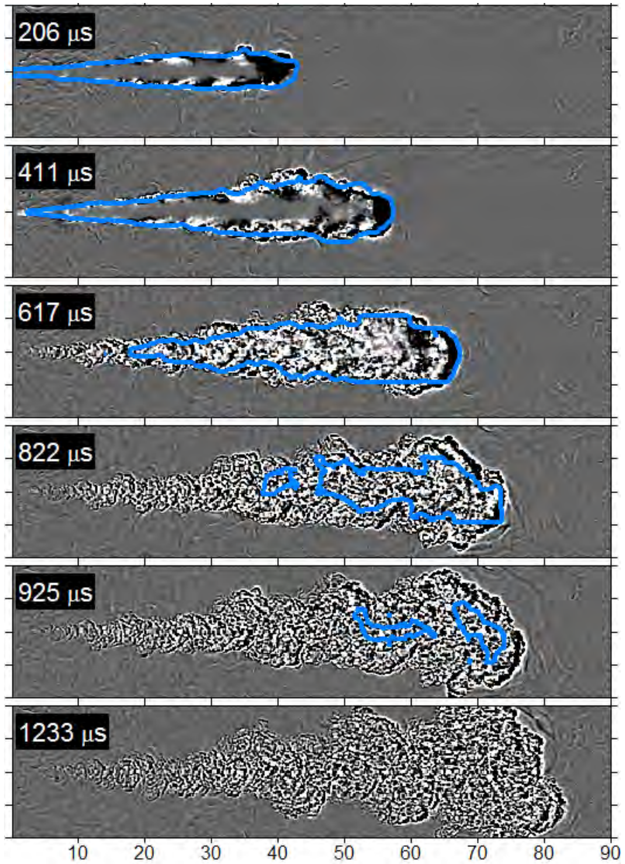
Partners

- 15 Industry partners in the Advanced Engine Combustion MOU
- >20 participants in Engine Combustion Network
  - Experimental and modeling
- Project lead: Sandia
  - Lyle Pickett (PI)

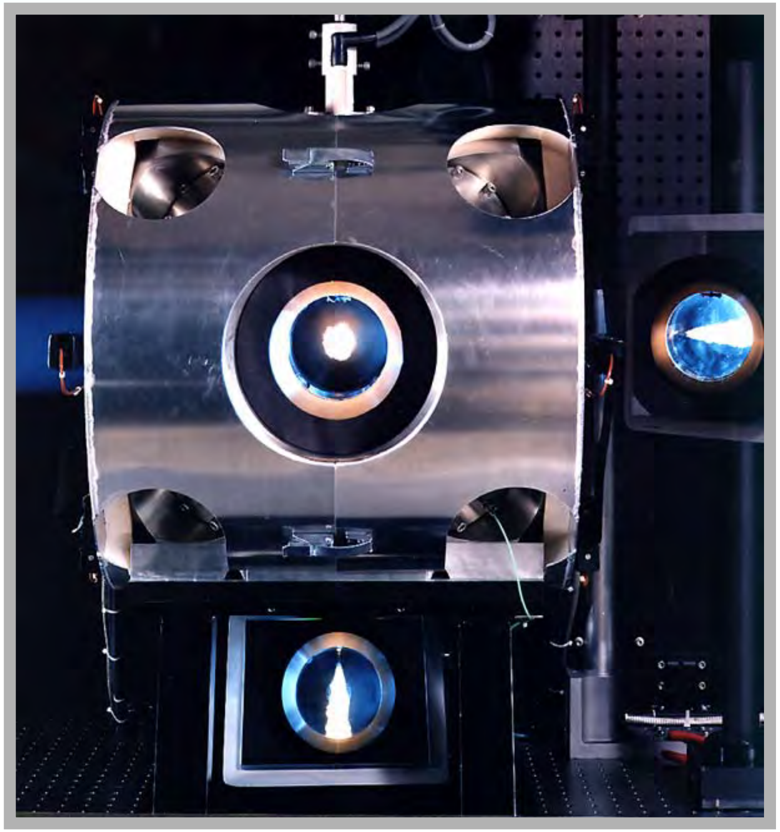
The role of spray combustion research for high-efficiency engines.

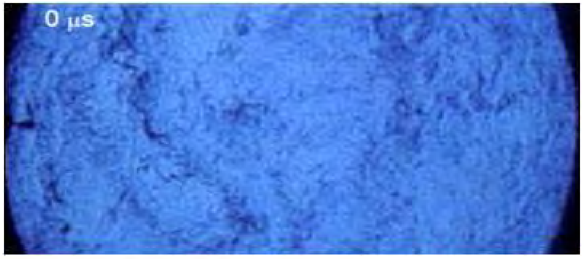
- Future high-efficiency engines use direct injection.
  - Diesel, gasoline direct injection, partially-premixed compression ignition.
- Complex interactions between sprays, mixing, and chemistry.
  - Multiple injections
  - Mixing driven by spray
  - Two-phase system
  - Complicated internal flows within injectors
- Optimum engine designs discovered only when spray modeling becomes predictive.

Schlieren: vapor boundary
BLUE: liquid boundary



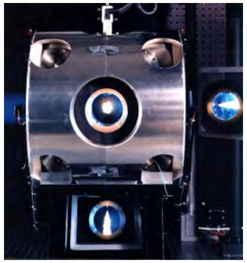
Studies of spray combustion in constant-volume chamber.

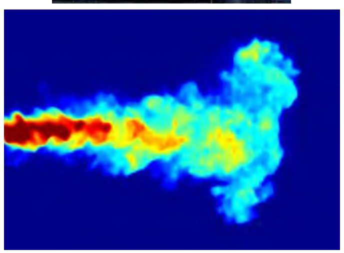


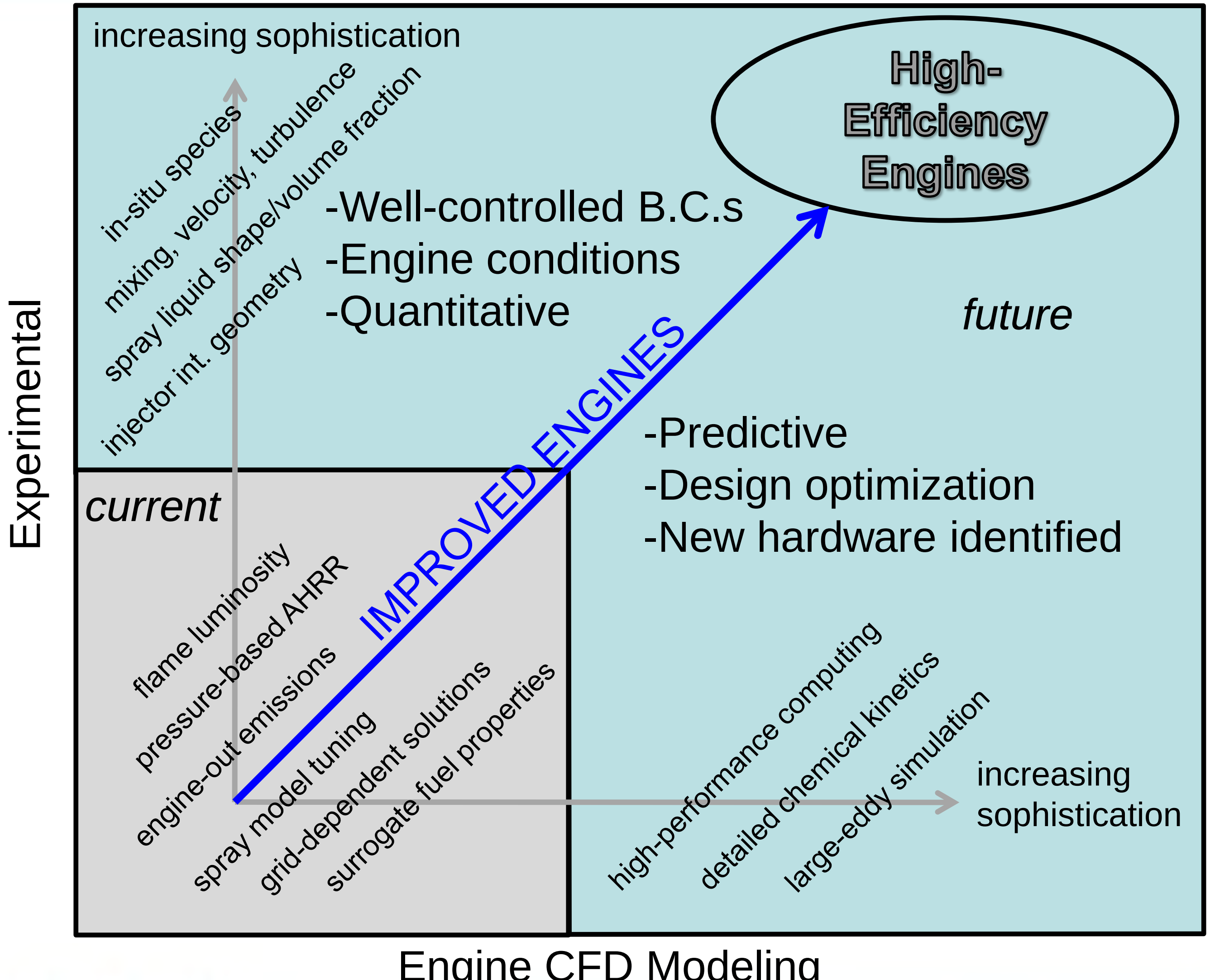


- Well-defined ambient conditions:
  - 300 to 1300 K
  - up to 350 bar
  - 0-21% O_2 (EGR)
- Injector
  - single or multi-hole injectors
  - diesel or gasoline (cross-cut)
- Full optical access
  - 100 mm on a side
- Boundary condition control needed for CFD model development and validation.
  - Better control than an engine.
  - Easier to grid.

A combined experimental/modeling pathway towards clean, high-efficiency engines.





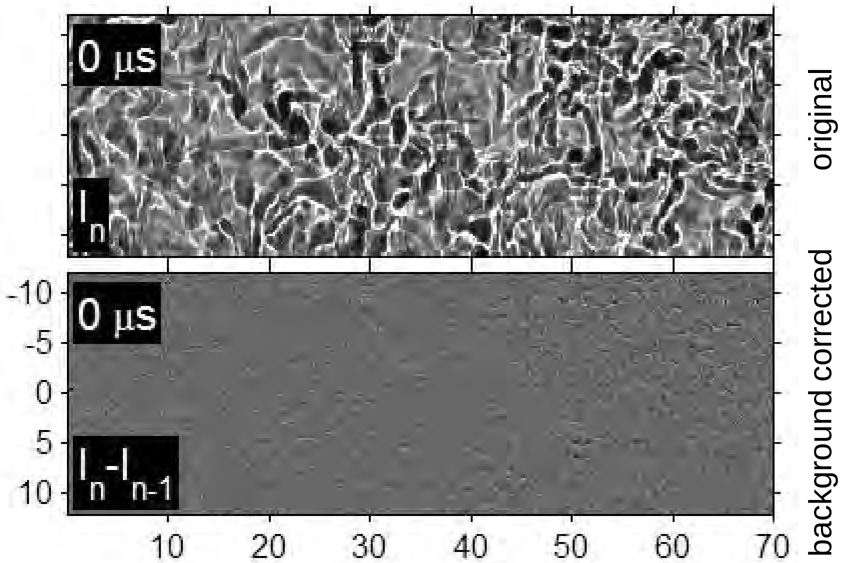


Objectives/Milestones

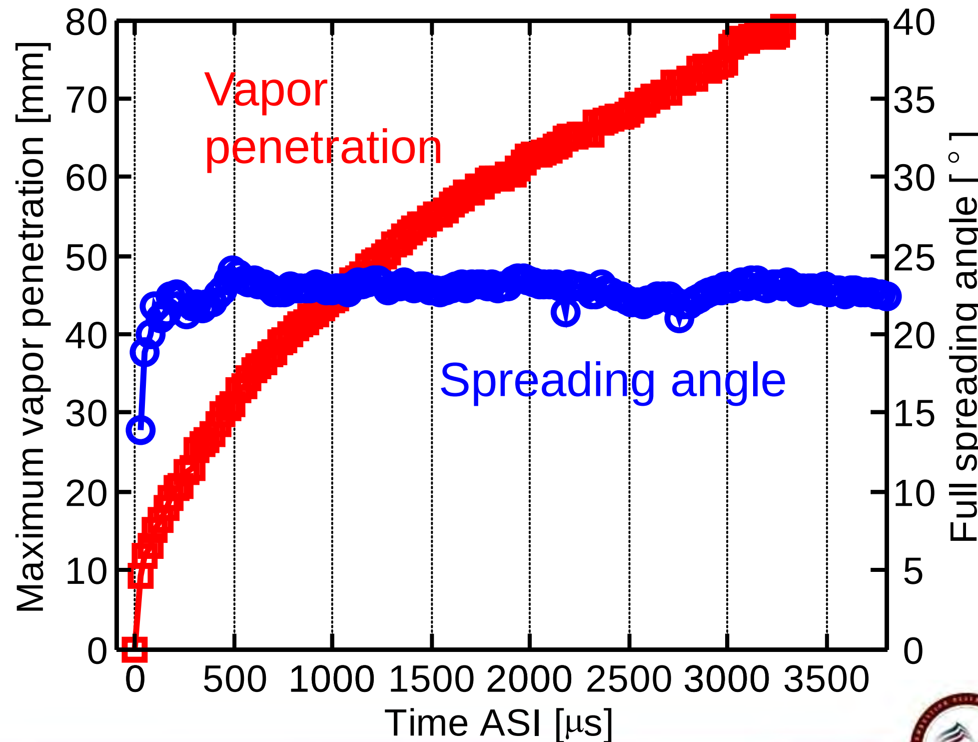
- Aid the development of computational models for engine design and optimization (ongoing).
  - FY11(1): Evaluate mixing processes in sprays in comparison to models using quantitative fuel vapor measurements.
  - Experimental and modeling collaboration through the Engine Combustion Network: http://www.sandia.gov/ECN
  - FY10-FY11(2): Develop "Spray A" diesel dataset at high-temperature, high-pressure condition.
- Identify combustion regime for gasoline direct injection, spark and autoignition (new project for FY11).
  - Direct injection of gasoline shows promise for LTC with lower heat-release rate.
  - FY11 (3): Use laser ignition, and autoignition, to identify if combustion is by flame propagation or self ignition.

(1) Measured "global" properties of spray need further understanding in comparison to CFD.

High-speed schlieren imaging (vapor)

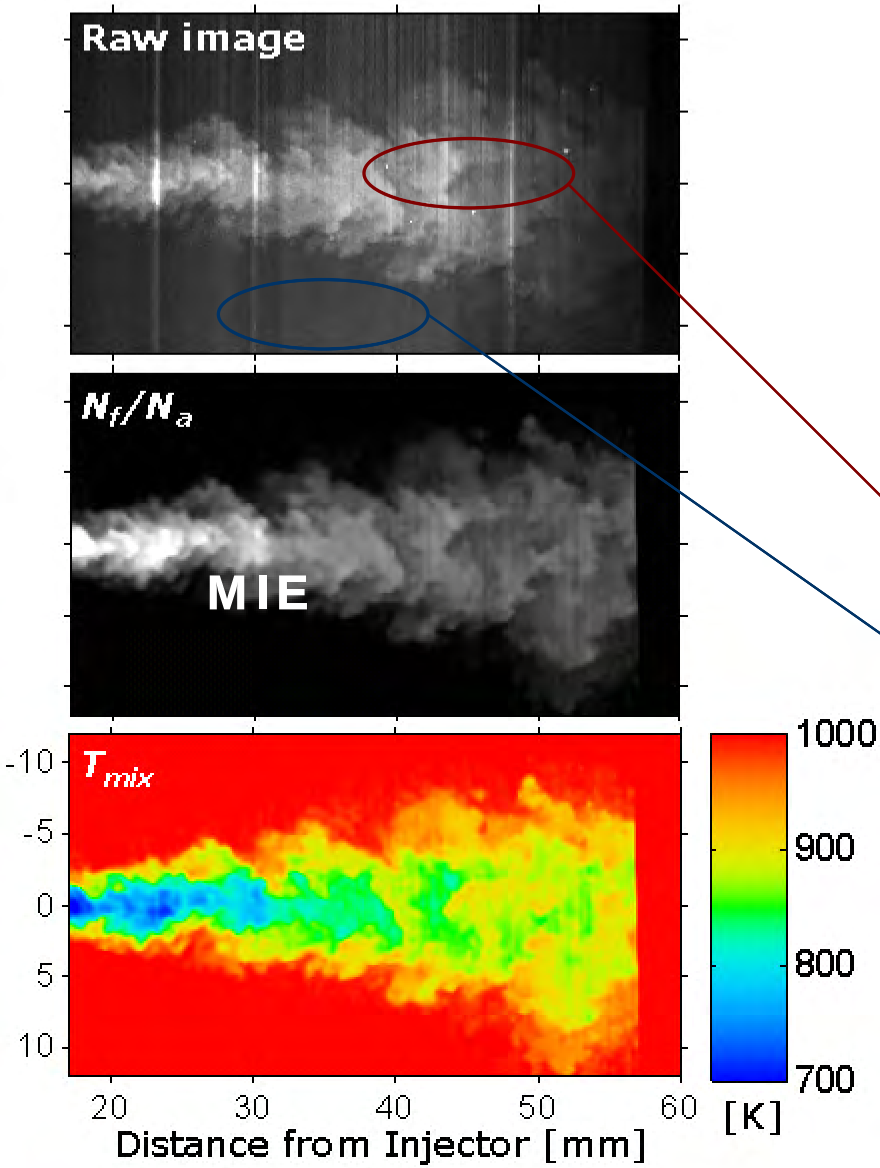


- Spreading angle derived from vapor boundary (green), at ½ jet penetration distance (Naber, 1996).
- Measured spreading angle depends somewhat on schlieren optical setup.



<u>Experimental Conditions</u>
"Spray A"
900 K gas temperature
22.8 kg/m^3 gas density
0% O_2-inert
1500 bar injection pressure
0.090 mm nozzle orifice
n-dodecane

Quantitative mixing diagnostic in harsh high-temperature, high-pressure environment.



- Use Rayleigh scattering in vapor portion of fuel jet.
  - Overcomes significant temperature/composition uncertainties compared to laser-induced fluorescence.
- Measure both $I_{R,a}$, $I_{R,j}$
  - Allows in-situ calibration for $I_{R,a}$ variation in laser sheet intensity.
  - Beam-steering or divergence addressed by using $I_{R,a}$ on bottom and top of jet.

$$\frac{I_{R,j}}{I_{R,a}} = \left(\frac{\sigma_f/\sigma_a + N_a/N_f}{1 + N_a/N_f} \right) \frac{T_a}{T_{mix}}$$

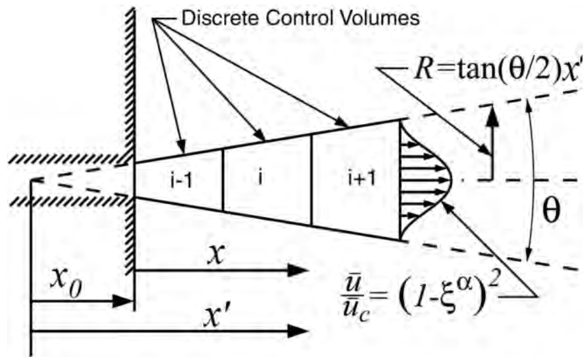
$$T_{mix} = f(N_a/N_f)$$

- Measurement provides
  - Fuel mixture fraction (mass fraction)
  - Mixture temperature

When modeled* penetration matches experiment, modeled mixing is also accurate.

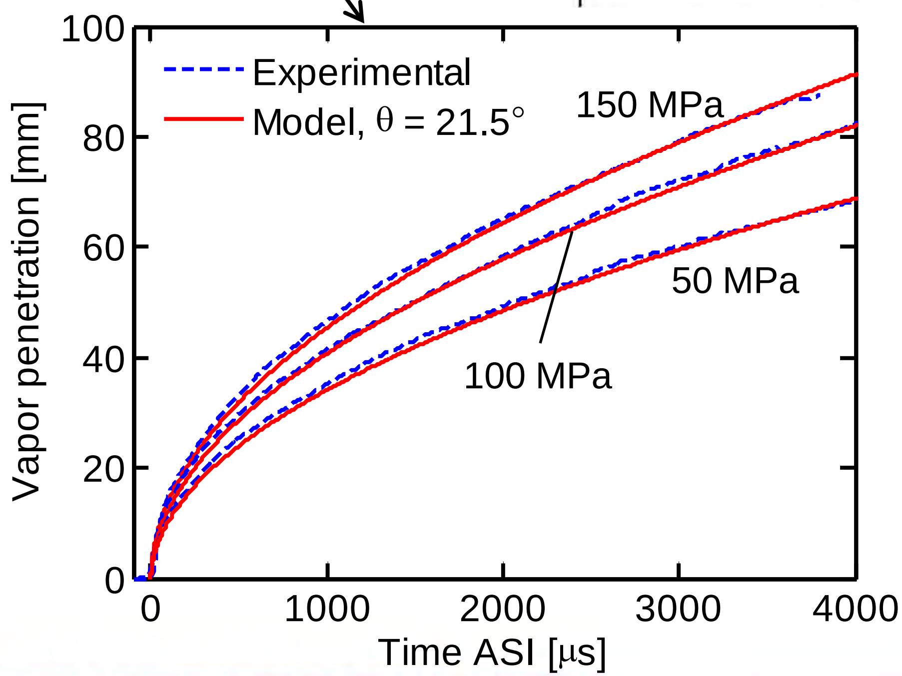
*Variable radial profile (Musculus and Kattke 2009)

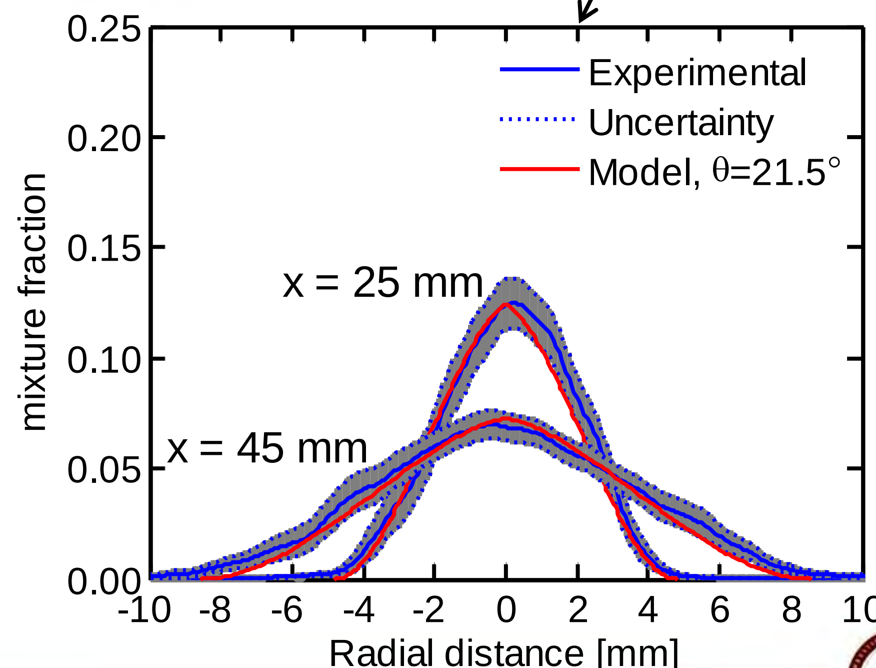
Spreading-angle adjusted to match experimental (schlieren) penetration rate.



Model predictions of mixture fraction (same spreading angle) agree with experimental Rayleigh measurements.

(see SAE 2011-01-0686)

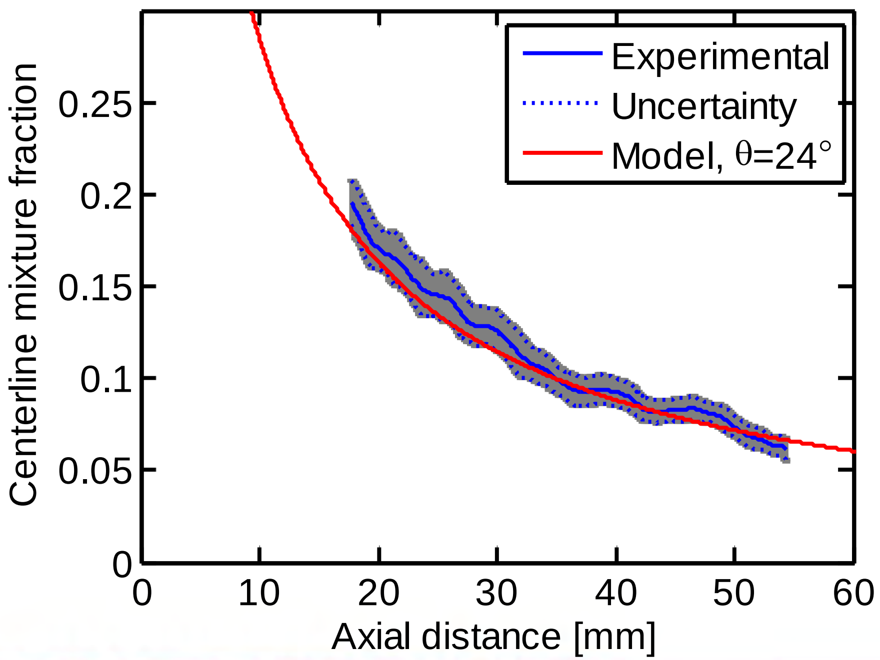


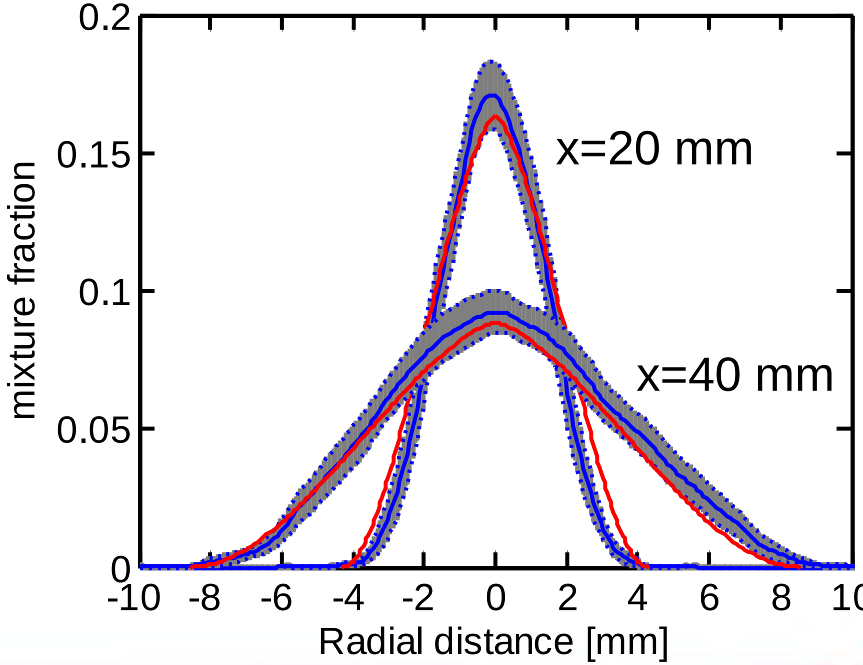


Mixing results confirmed at other injector and ambient operating conditions.

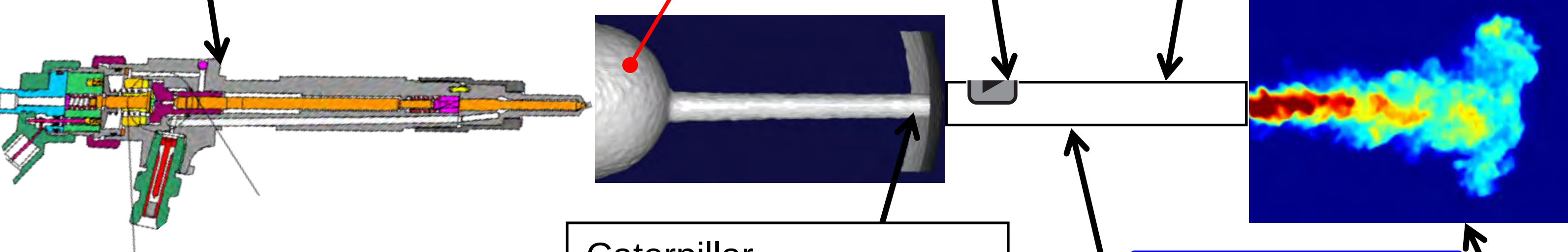
- Mixture distribution shows self-similar, 1/x decay
  - Such behavior is typical of gas jets.
  - Documented now for the first time in diesel sprays at engine conditions.

Experimental Conditions
1000 K gas temperature
14.8 kg/m^3 gas density
0% O_2-inert
1540 bar injection pressure
0.100 mm nozzle orifice
n-heptane





(2) Industrial and academic collaboration in the Engine Combustion Network for "Spray A"



- Operation at the same injector and ambient conditions.
- Voluntary participation
- Led by Sandia.

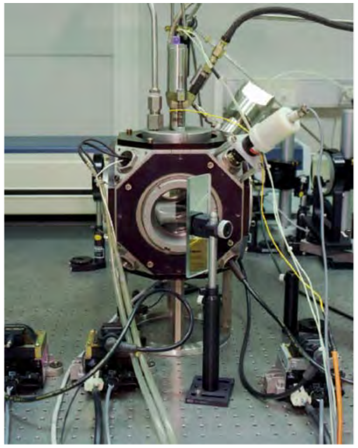
Experimental participation at Spray A

Institution	Facilities	Personnel
Sandia	Preburn CV	Lyle Pickett
IFPEN	Preburn CV	Gilles Bruneaux, Louis-Marie Malbec
CMT	Cold CV, Flow PV	Julien Manin, Raul Payri
Chalmers	Flow PV	Mark Linne
GM	Flow PV	Scott Parrish
Mich. Tech. U.	Preburn CV	Jeff Naber, Jaclyn Nesbitt, Chris Morgan
Argonne	Cold V, X-ray Sync.	Chris Powell, Alan Kastengren
Caterpillar	Flow PV	Tim Bazyn, Glen Martin
Aachen	Flow PV	Heinz Pitsch, Joachim Beeckmann
Meiji U.	Preburn CV	Tetsuya Aizawa
Seoul Nat. U.	Preburn CV	Kyoungdoug Min
Eindhoven U.	Preburn CV	Maarten Meijor, Bart Somers

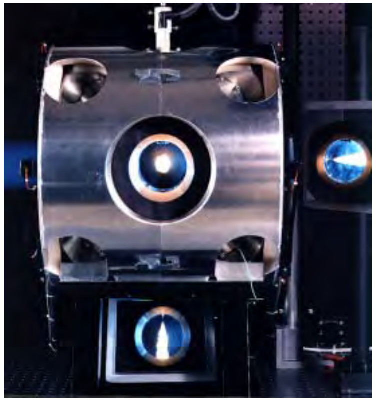
BLUE: In progress Red: Commencing in next 3 months.

Spray A vapor penetration shows reasonable agreement at 4 different institutions.

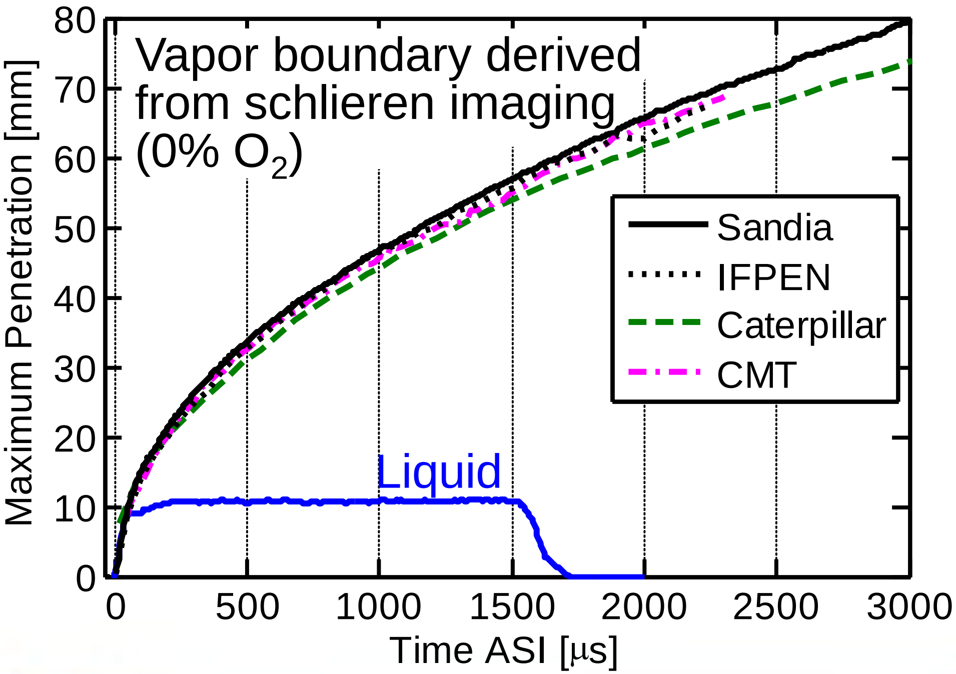
IFP



Sandia

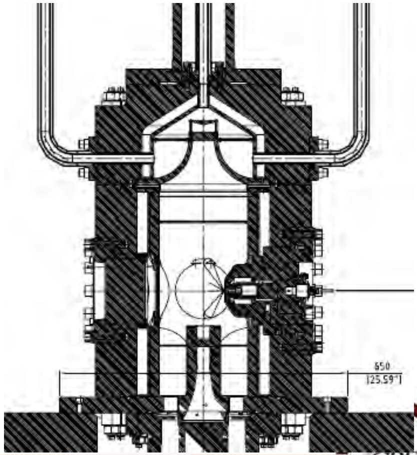


- Despite the significant challenge to control high-T, high-P boundary conditions.
- Ongoing work to understand the sources of discrepancy, including post-processing.
- Leveraging experimental work is possible!



CMT

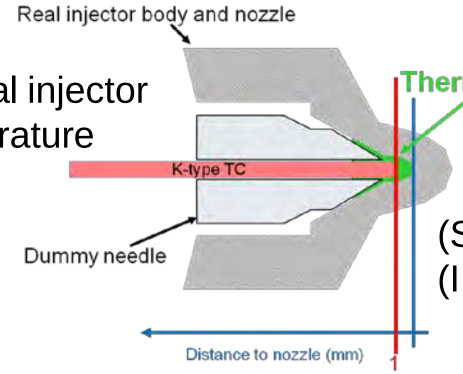
Caterpillar



ECN research accelerates detailed (quantitative) understanding of engine sprays.

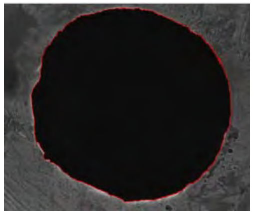
- Other activities during FY11:
  - Comparison of rate of injection and rate of momentum at different institutions.
  - Preburn vs. heated flow chambers.
  - Internal injector tip temperature.
  - Internal shape of nozzle by x-ray tomography and silicone molds.
  - Consistent measurement/ quantification of liquid length and volume fraction.
  - Measurement of cool flame, ignition site, and lift-off length.
  - …many others now available on web. Download data at www.sandia.gov/ECN
- ECN workshop held to coordinate experimental/modeling activities.
  - May 13-14, Ventura, CA, before ILASS.
  - 60 participants; >50% attendees use ECN data for CFD model development.

Internal injector temperature



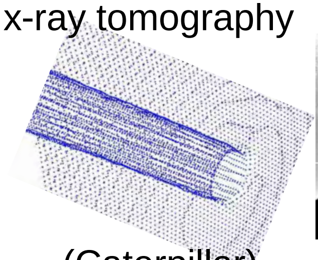
(Sandia)
(IFPEN)

SEM



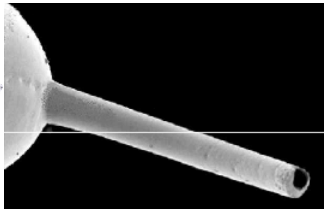
(Sandia)

x-ray tomography



(Caterpillar)

silicone mold

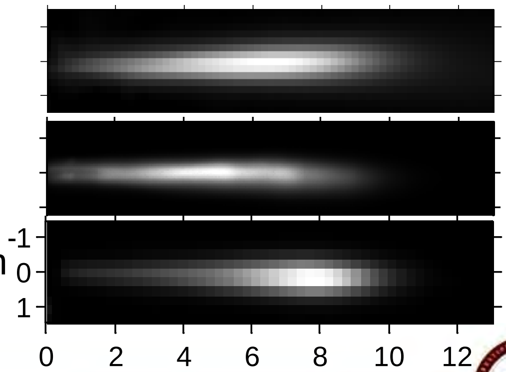


(CMT)

Back-illumination optical thickness

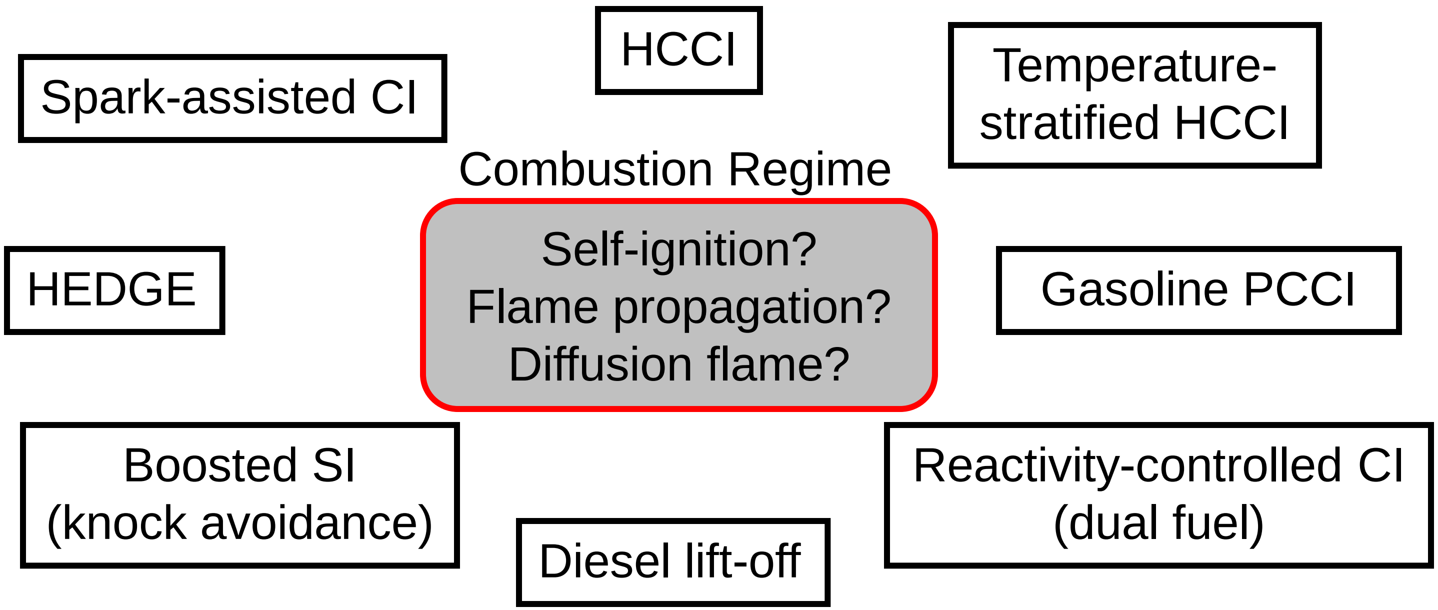
Side-illumination Mie scatter

Head-illumination Mie scatter



(Sandia)

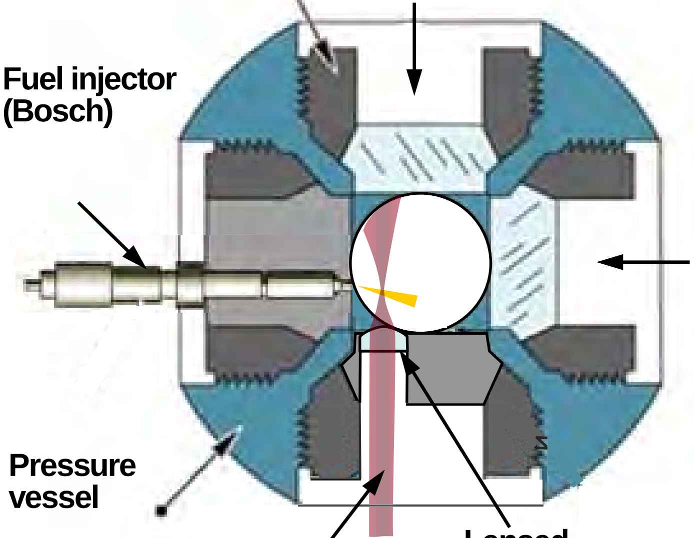
(3) Breakthroughs in engine efficiency require better understanding, modeling, and control.



- Strategies navigate combustion regimes that tend to have high heat-release rate (noise) and high UHC and CO emissions
  - Can we slow down combustion, maintain control, and still retain high efficiency?
  - Can we model these processes accurately, including crossover from one regime to the other?
- Approach: Characterize transition combustion regime from flame propagation to autoignition in gasoline sprays.

2-hole gasoline injector experimental setup

Constant-volume chamber

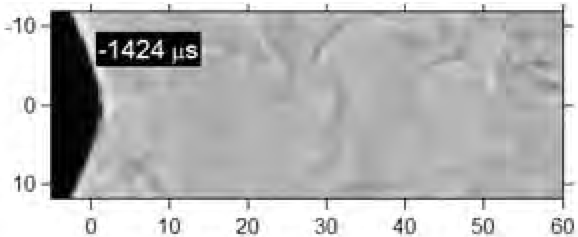


GDI fuel injector (Bosch):	2-hole
Nominal flow rate at 100 bar	3.75 cc/s
Inner hole diameter	0.125 mm
Nominal spray included angle	60°
Fuel injection pressure	100 bar

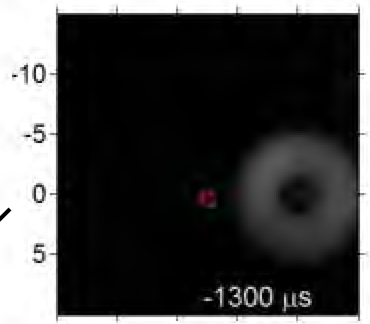
Engine Params.
CR = 12
P_BDC = 1 bar
T_BDC = 340 K

-30 CAD Conditions
T_a = 700 K
ρ_a = 6.5 kg/m^3
P = 13 bar
21% oxygen (air)

Schlieren imaging (vapor)
(Side view)



(Front view)

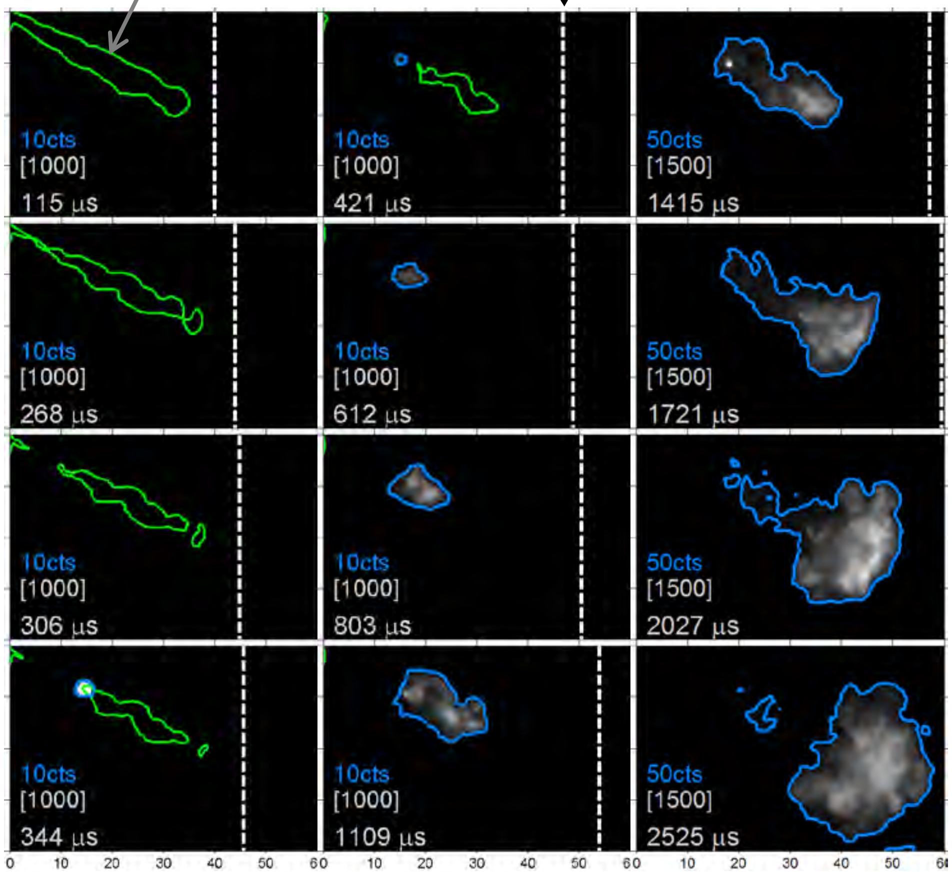


Mie-scatter imaging (liquid)
(Bottom view)

Laser ignition AEI produces flame that propagates into downstream richer mixture.

Vapor border from schlieren

Liquid border

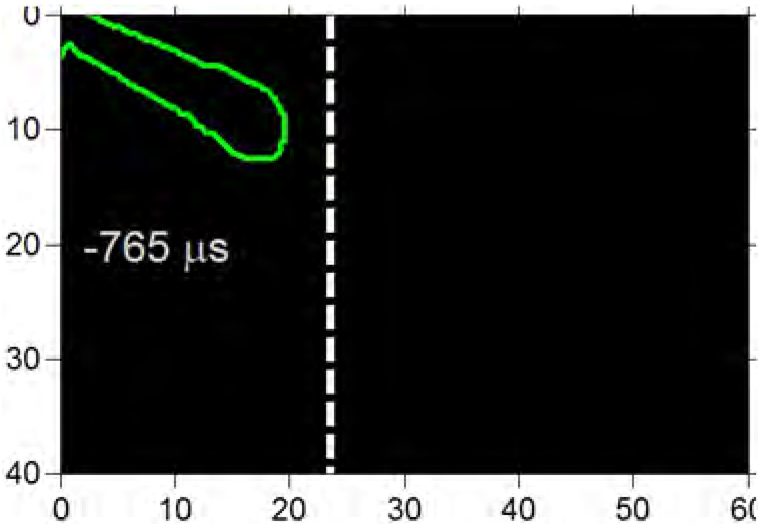


<u>Laser Ignition Conditions</u>

T_a = 700 K

ρ_a = 6.5 kg/m^3

AEI_{laser} = 350 µs

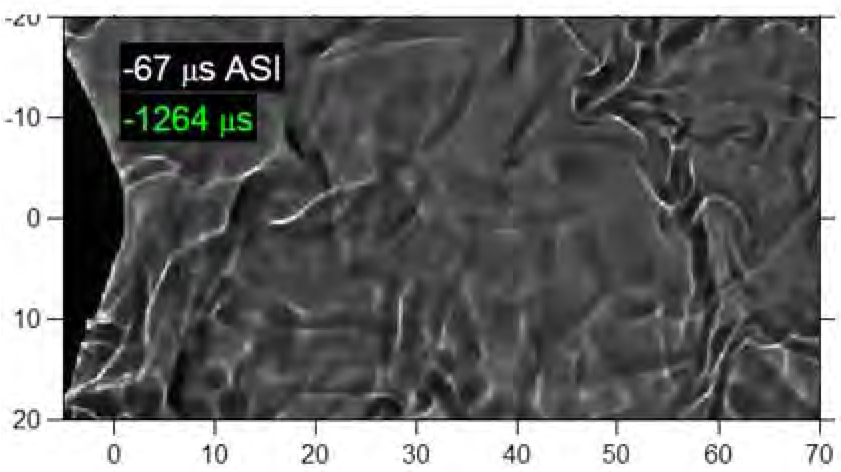


Raising ambient temperature produces a connected reaction zone AFTER autoignition.

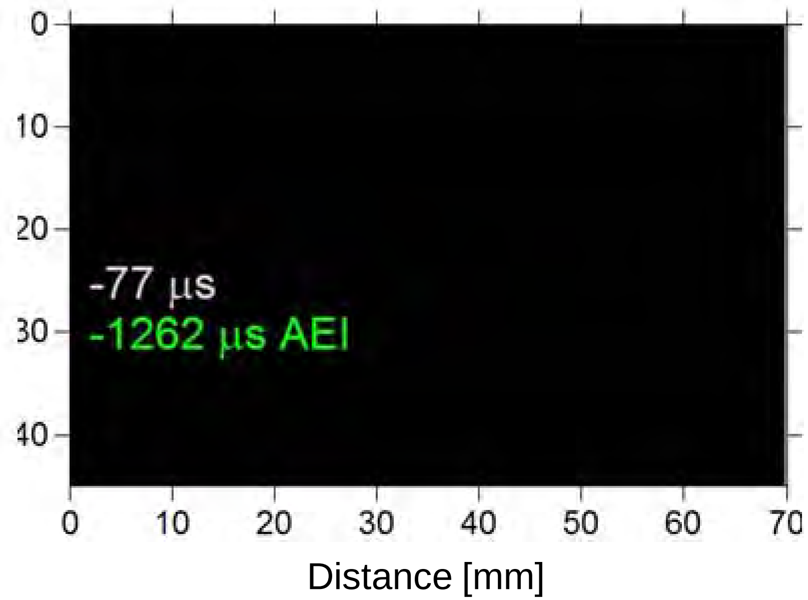
<u>Auto Ignition Conditions</u>
T_a = 1100 K (ambient)
ρ_a = 6.5 kg/m^3
P = 20.5 bar

<u>Ignition Time/Location</u>
2100 μs ASI
900 μs AEI
20 mm downstream

Schlieren imaging (vapor and flame)
(+ higher sensitivity)

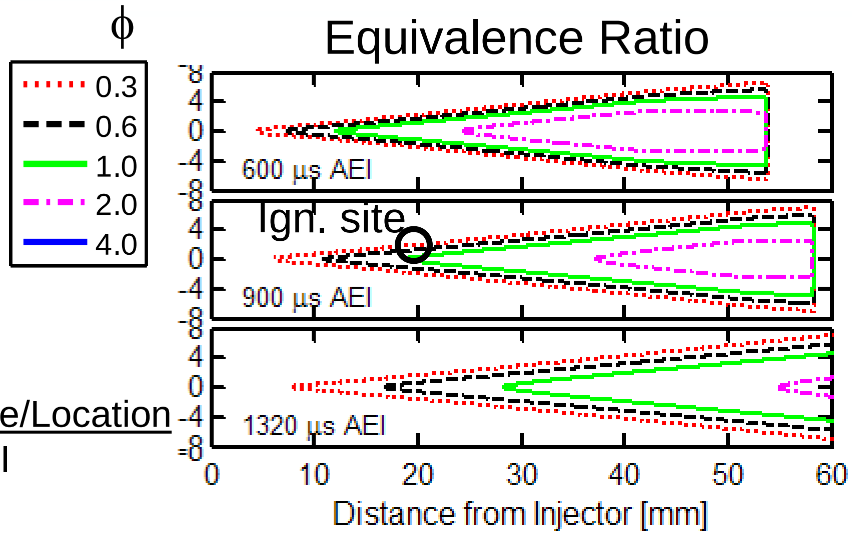


Mie scatter + Chemiluminescence
(bottom view)

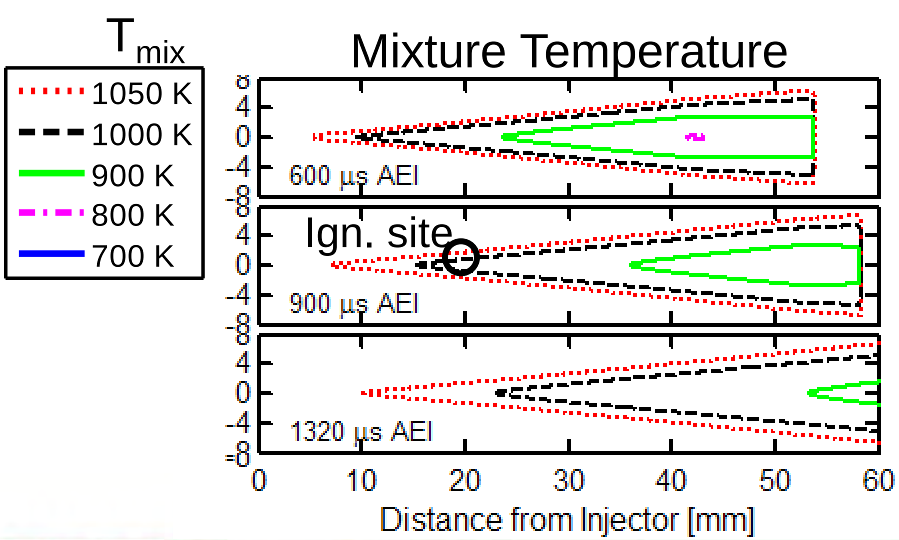


- OPPOSITE the order of spark-assist CI.
- Flame catches up with most/all of charge.
- SMOOTH heat release; also no soot.

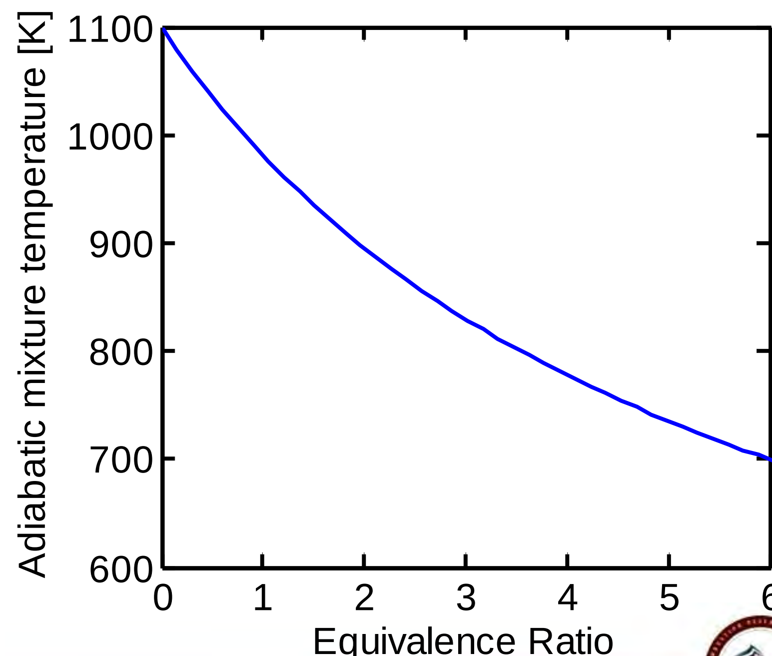
Mixture equivalence ratio, residence time, and temperature ALL affect ignition.



<u>Ignition Time/Location</u>
2100 μs ASI
900 μs AEI
20 mm



- Flame propagation is possible after self-ignition because of the highly stratified (cool, high ϕ) charge surrounding the ignition location.



Future work

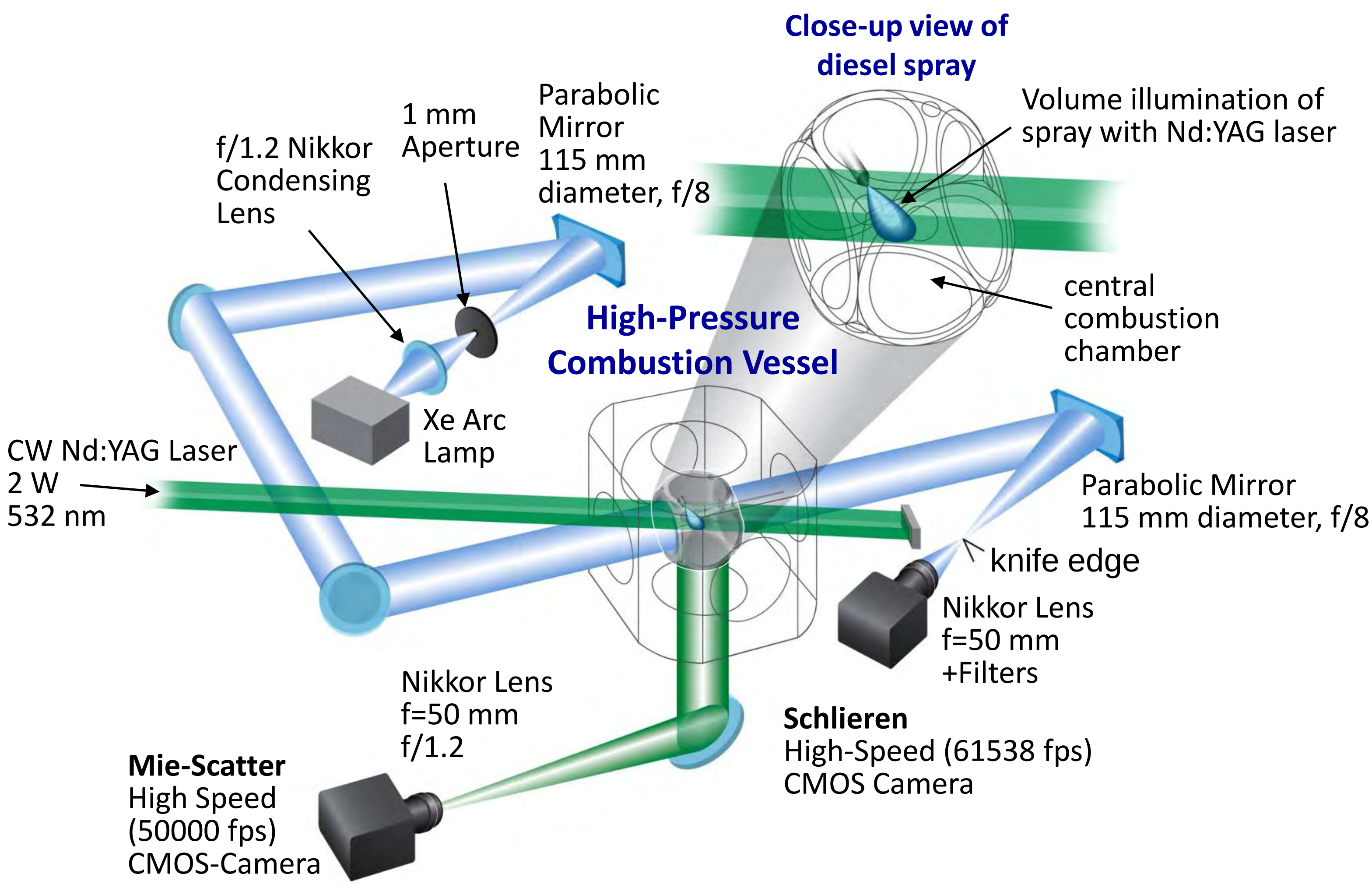
- Outlook for the Engine Combustion Network
  - Measurements (not a complete list, Sandia in blue):
    - Nozzle shape
    - Internal needle movement
    - Discharge and area contraction coefficients
    - Rate of injection
    - Near-nozzle liquid volume fraction
    - Droplet size, velocity, shape
    - Maximum liquid penetration
    - Vapor penetration rate
    - Velocity and turbulence within spray
    - Mixture fraction (non-reacting and reacting)
    - Ignition delay
    - Cool flame position and timing
    - Heat-release rate
    - Quantitative soot, soot precursor distribution
    - Lift-off length
  - Side-hole spray compared to axial hole
  - Liquid volume fraction near the liquid length
  - Parametric variation in ambient temperature and injection pressure
  - ECN Workshop will coordinate modeling efforts and establish future direction
- Gasoline direct-injection sprays
  - Develop an ECN-type research effort to quantify mixing, liquid distribution at various target conditions.
  - Identify regimes with both autoignition and flame propagation (relevant to knock).
  - Use high-pressure diesel and low-pressure SIDI-type injectors.

Presentation Summary

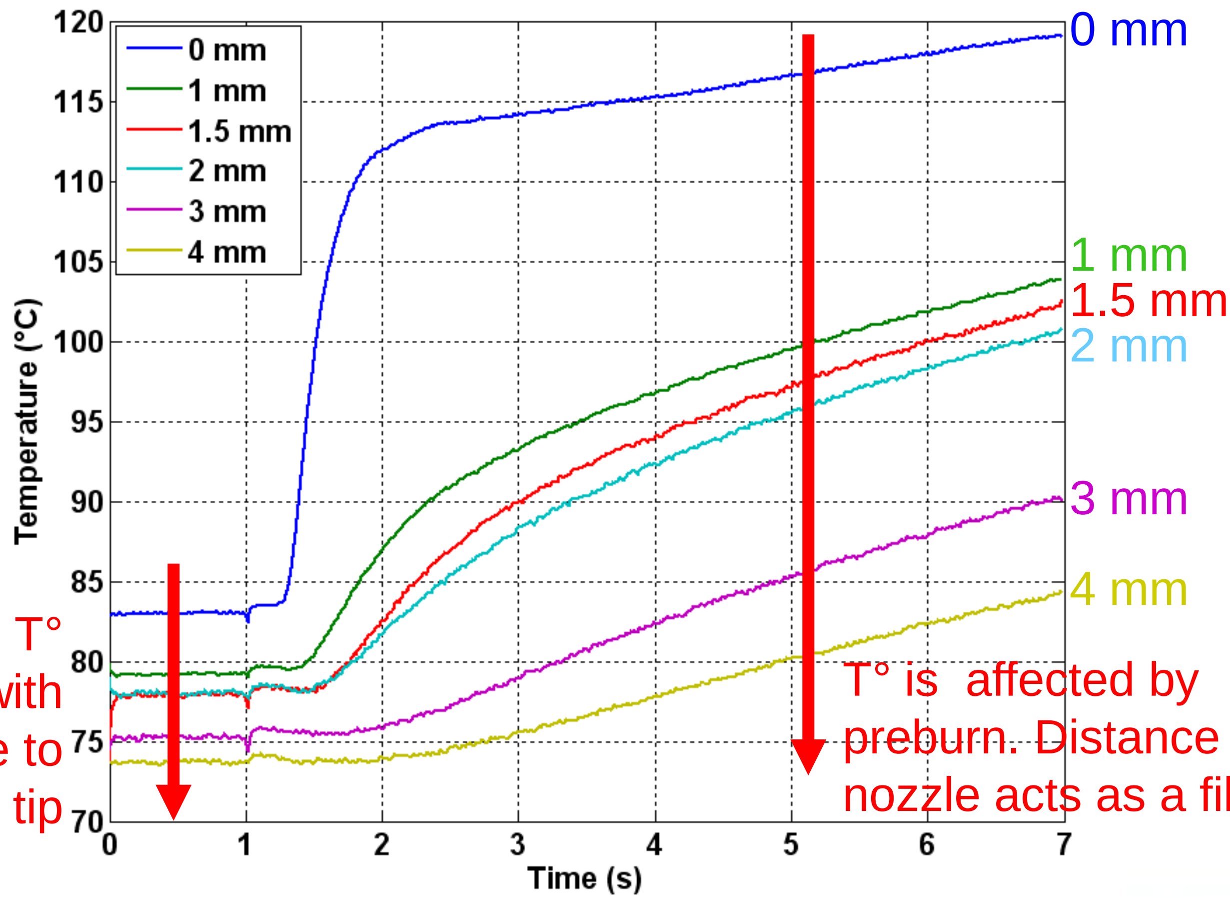
- Project is relevant to the development of high-efficiency, low-emission engines.
  - Observations of combustion in controlled environment lead to improved understanding/models for engine development.
- FY11 approach addresses high-efficiency diesel and gasoline concepts.
  - Quantitative mixture fraction data permit model calibration, and relate global penetration rate to mixture distribution.
  - Massive Spray A dataset is being generated, which will be a key component for future model improvement.
  - Flame propagation AFTER autoignition observed in gasoline sprays at high ambient temperature.
  - Utilizing flame propagation after autoignition may be important for slowing heat release and controlling LTC.
- Collaboration expanded to accelerate research and provide greatest impact (MOU, leading Engine Combustion Network).
- Future plans will continue ECN-type diesel and gasoline research.

Technical Backup Slides

Optical diagnostics experimental setup



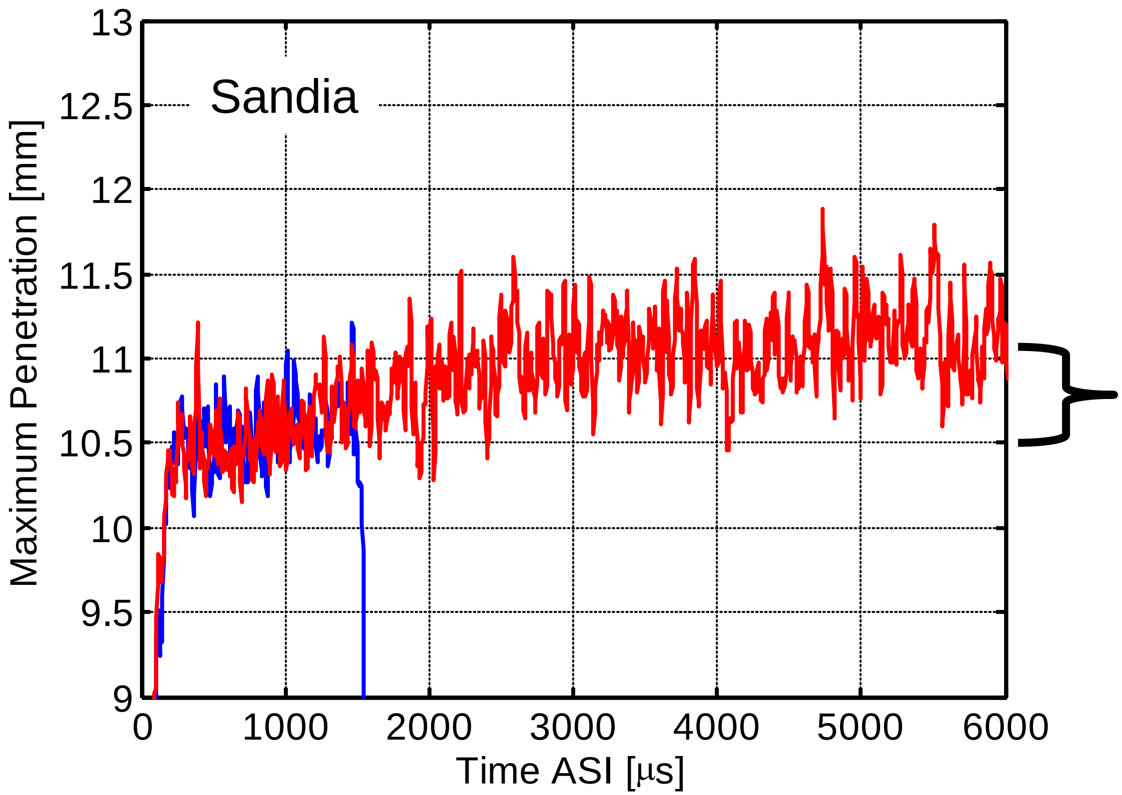
Internal injector temperature distribution



Steady state T° decreases with distance to nozzle tip

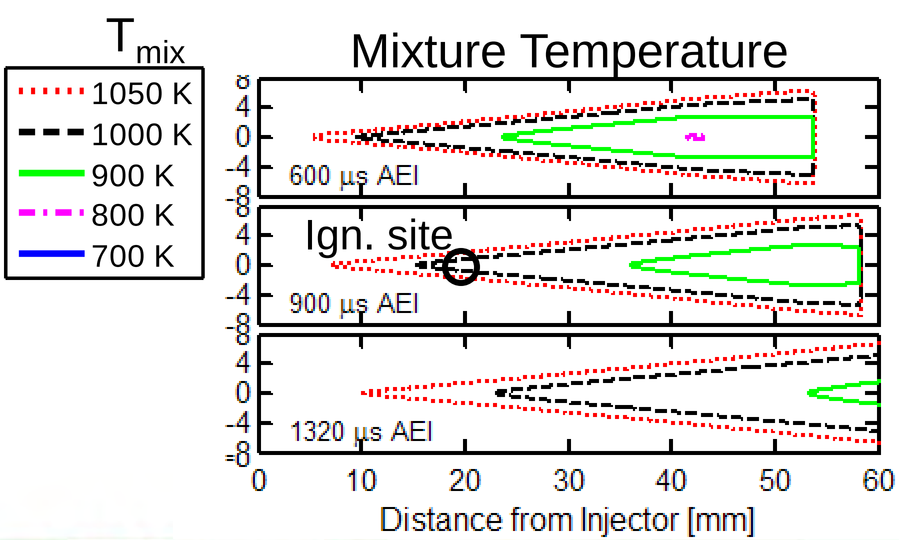
T° is affected by preburn. Distance to nozzle acts as a filter.

Liquid length increases slightly with increasing time after start of injection.



- Suggests that fuel cools the injector tip with increasing time ASI.
- 0.5 mm → approx. 20° C.

Analysis shows that the typical ignition site is near 20 mm. Why?



- Mixing near injector after the end of injection affects ϕ and T.
- Equivalence ratios near unity.
- High mixture temperatures, near 1000 K.
- Long residence time.
  - Some of “first-injected” fuel appears to be shed in large-scale structures to the side of the jet.
  - “First-injected” fuel has 1200 μs (the inj. dur.) longer residence time than “last-injected”.
  - Last-injected fuel goes to head of jet.