Laser Based Spark Ignition for Reciprocating Engines

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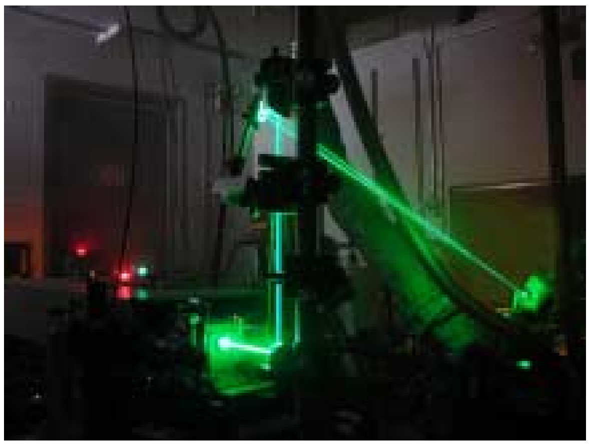


September 16, 2002

Natural Gas Infrastructure Reliability Industry Forums

Introduction: *Why Laser Ignition?*

- Regulations on NOx Emissions Have continue to force Operation of Natural Gas Engines to Leaner Air/Fuel Ratios
- Lean Air/Fuel Ratios Are More Difficult to Ignite, Conventional Systems Require High Ignition Energies
- Natural Gas Is More Difficult to Ignite Than Gasoline due to the Strong C-H Bond Energy
  - **Laser Light Is Monochromatic, So Selective Chemistry Becomes a Possible Option.**
- Due to Increased Ignition Coil Energy, Spark Plug Service Life Is Very Low for Natural Gas Engines
  - **Laser ignition offers the potential for extended service life**
- Rugged lasers are available for numerous industrial processes
- **Potential for Improved Durability!**

Introduction: *Why Laser Ignition?* cont.

- Engine Operation at Lean Air/Fuel Ratios Using Spark Plug Ignition Is Limited Due to <u>Misfire</u>, Ignition Delay and Unstable Ignition
  - **Again, lean a/f ratio operation pushes spark systems to higher energies, multiple firing or multiple locations are additional options**
- Ignition Sites of Spark Plug Ignition Are <u>Fixed</u> Within the Combustion Chamber
  - **For laser ignition, multiple-point ignition is achievable and optimum ignition sites can be selected**
- Spark Plug Electrodes <u>Interfere</u> With Propagation of the Early Combustion Flame, Compounding Ignition Problems
  - **Because of the non-intruding nature, laser ignition has minimum heat loss and flame quenching**
- **<u>Potential for Improved Engine Performance!</u>**

TECHNOLOGY STATUS

- Previous engine work was focused on laser ignition of gasoline (Dale, et al., 1979) , or propane (Smith, 1979) no work on laser ignition for a natural gas engine has been reported although Ma, et al., 1998, used a motored slider crank mechanism with methane.
- Past work has demonstrated increased flame speed and combustion pressure over conventional spark systems (Tran and others).
- Mass production of lasers at significantly reduced size and cost is imminent
- Understanding fundamental ignition phenomena in the context of laser radiation is required
- Transfer of laser ignition technology to single cylinder natural gas test engine is next step
- A commercial embodiment for a multi-cylinder engine laser ignition is the ultimate goal

Research Needs

- *Fundamental Level*
  - ***Basic science regarding ignition of combustible mixtures***
  - ***Multiple pulse ignition***
  - ***Multiple Point Ignition***

- *Practical Level: <u>Research Needs Leading to Commercialization</u>*
  - ***Laser induced optical damage/Beam Delivery***
  - ***Particle deposits***
  - ***Laser System***
  - ***Intelligent Control***
  - ***Laser Distribution***

Goals and Objectives

- **Develop scientific and engineering foundation for laser spark ignition in reciprocating engines**
  - Single Cylinder
  - Single Point Ignition
  - Laser beam distribution
  - Multipoint ignition
  - Multipulse ignition

NETL Activities

- **Task 1: Quiescent and Turbulent constant volume, high pressure combustion cell experiments**
- **Task 2: NETL-single cylinder engine experiments**
- **Task 3: Laser source selection and evaluation**
- **Task 4: Fiber Optics Beam delivery study**
- **Task 5: Optical window damage and cleaning**
- **Task 6: Integrated System Testing**

Summary of NETL Laser Ignition Work to-date

- Laser ignition tests using a constant volume cell and turbulent jet diffusion flames have been carried out
  - Investigated effects of optical properties and fuel properties on the ignition probability and the minimum ignition energy
  - Developed theoretical ignition model for laser ignition
  - Considered benefits of laser ignition and its potential applications for gas engines
  - Identified many technical difficulties and potential solutions

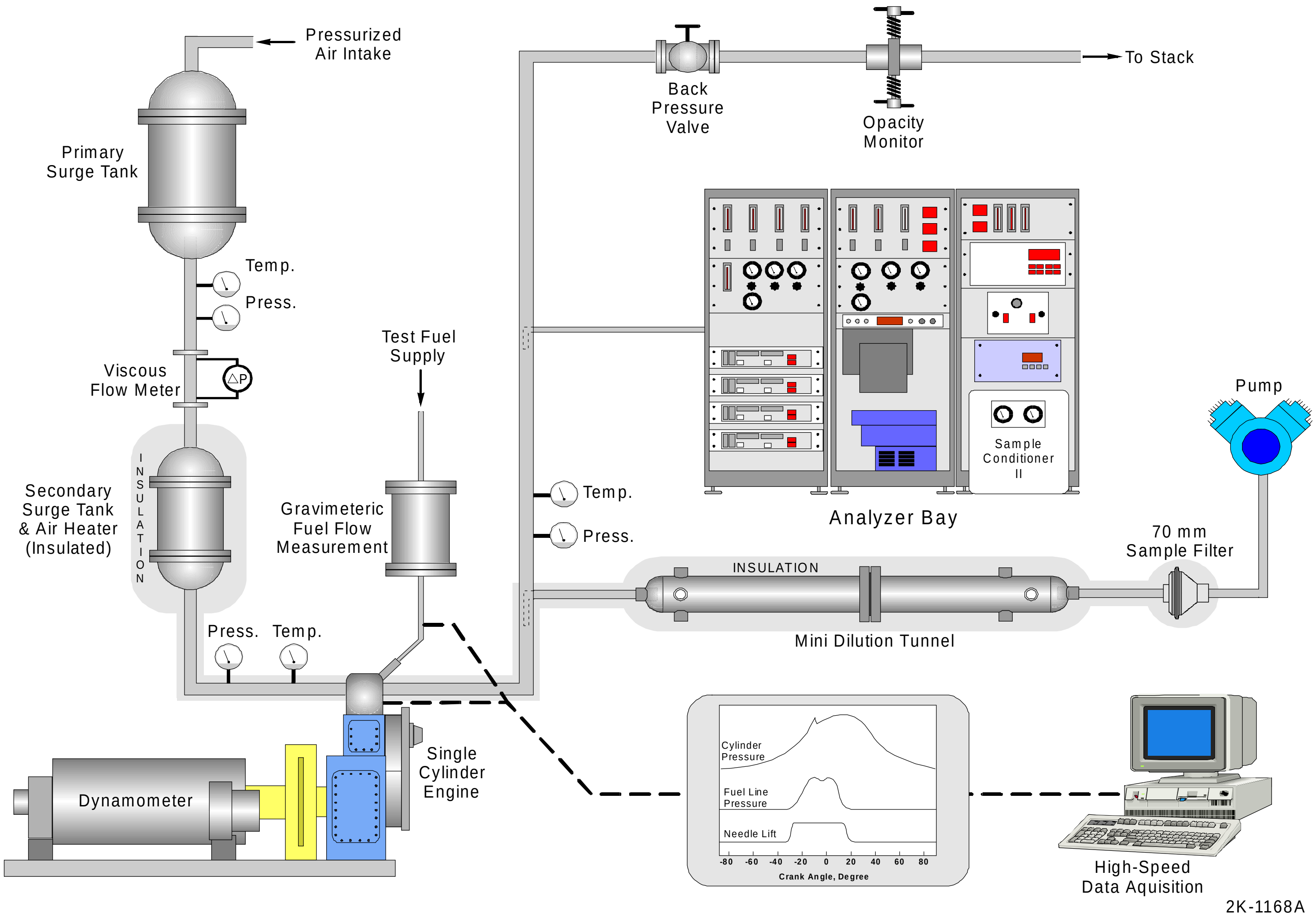
Summary of NETL Laser Ignition Work to-date (cont.)

- **Initial testing of a laser spark in an engine**

  - A comparison of engine emissions and combustion parameters using a Ricardo Proteous, single-cylinder, 4-stroke, spark ignited natural gas engine using both a conventional spark system and a laser spark system was conducted.

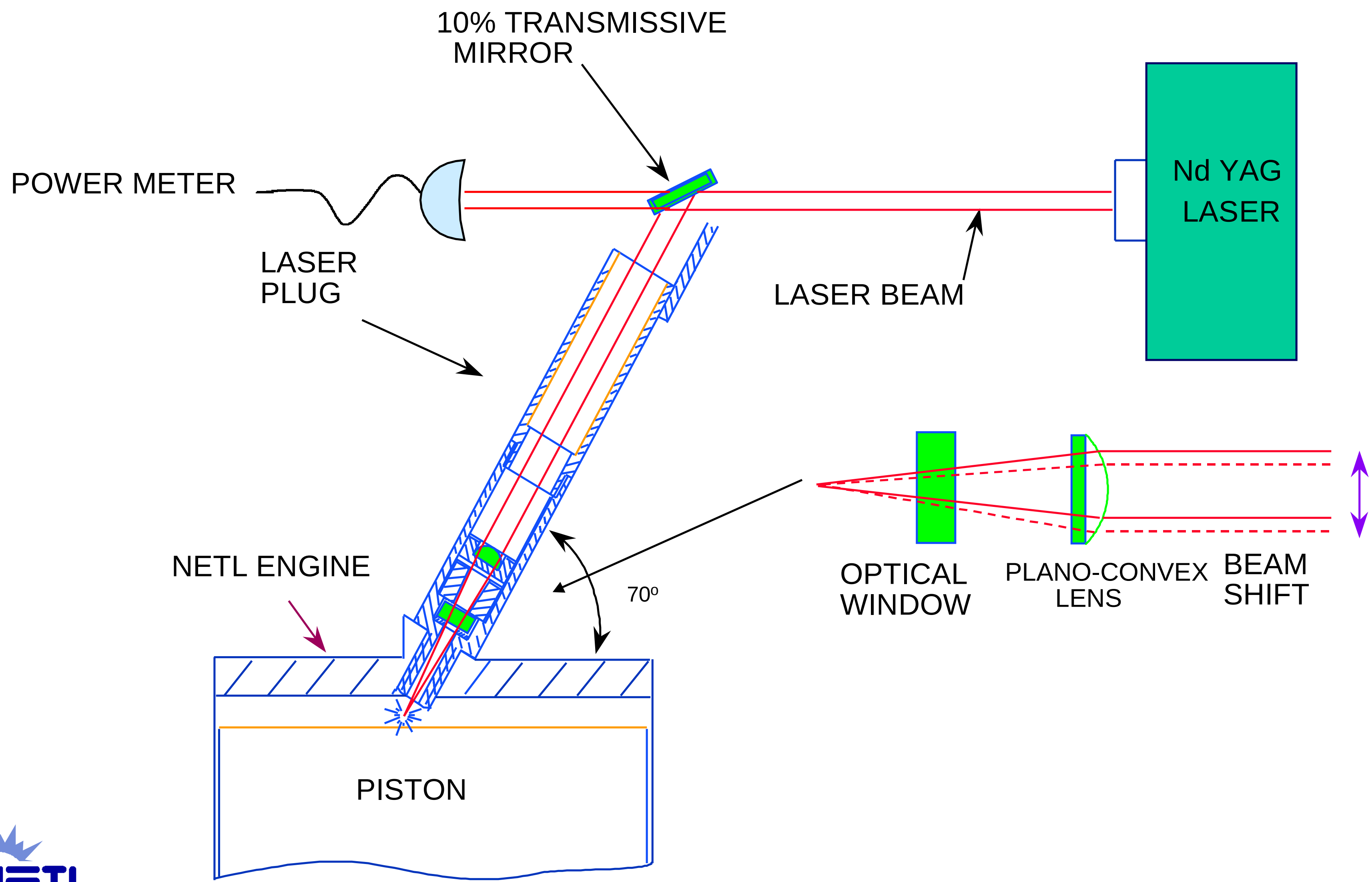
  - The engine was operated at a constant speed of 1200 rpm and at moderate load conditions. The emissions and combustion performance data for each ignition system at three equivalence ratios and three timing conditions were compared. Additional testing of the laser spark system at $\phi=0.5$ was also performed.

Engine Testbed Schematic



NETL

Laser Arrangement



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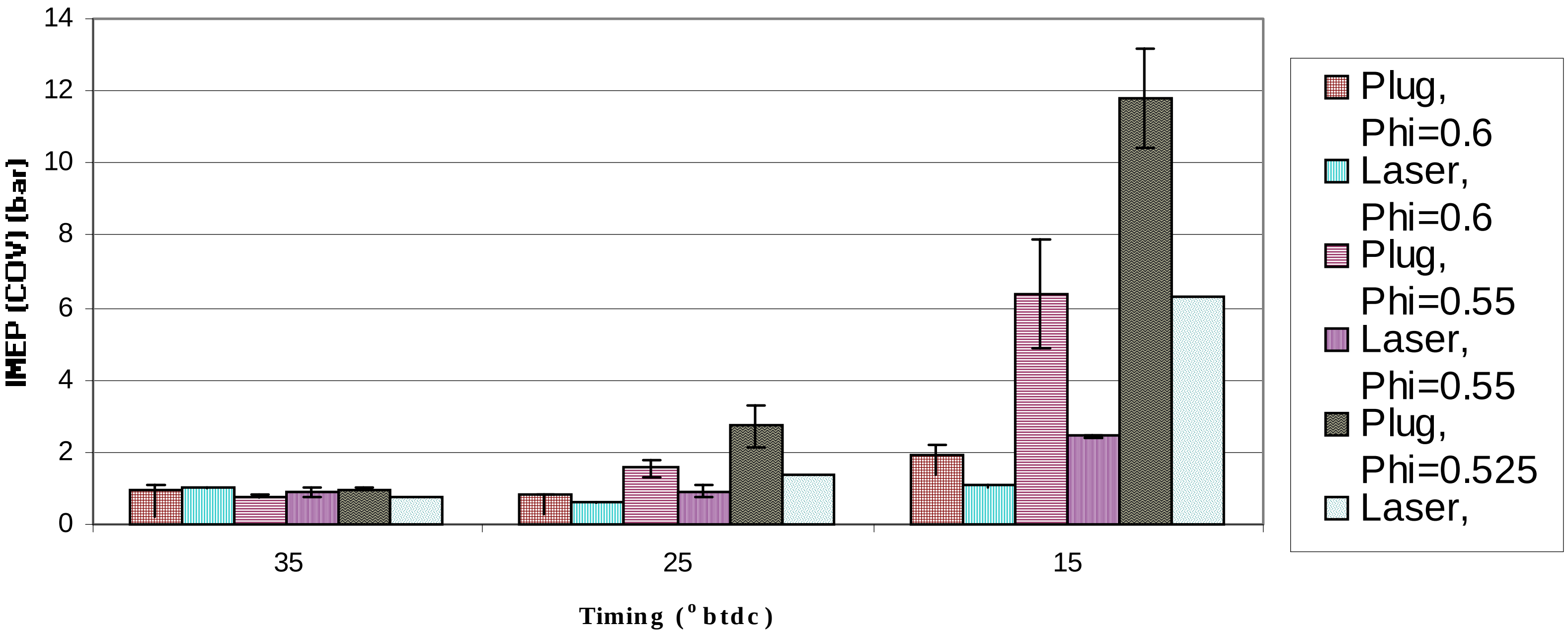
Initial Single Cylinder Engine Testing Results

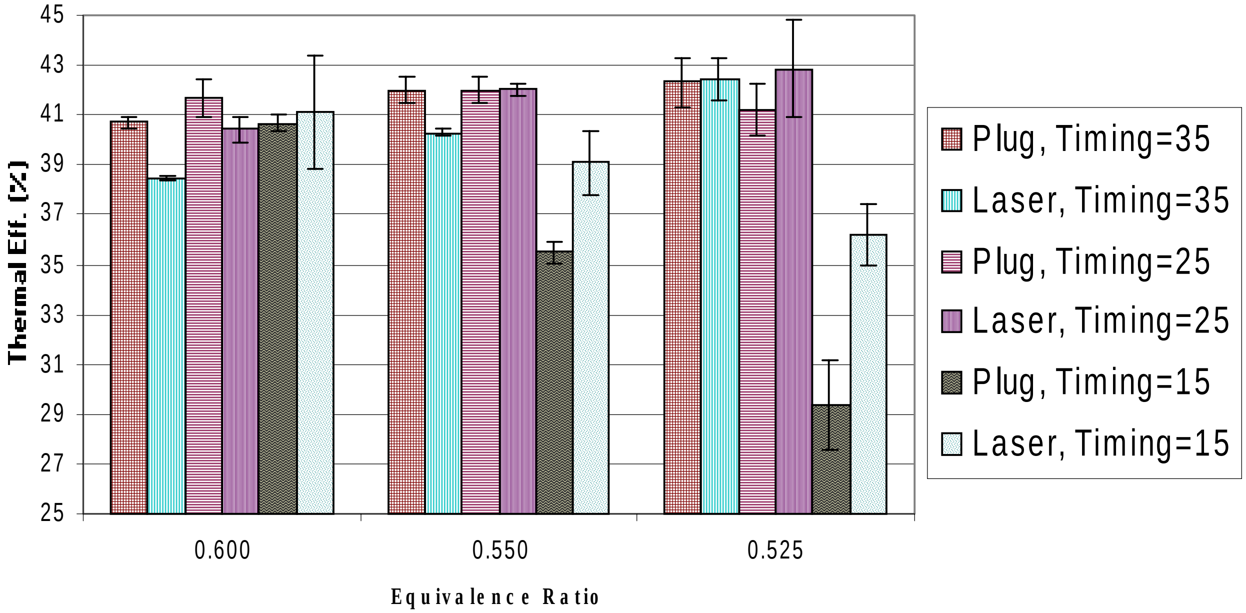
Coefficient of Variation (COV) of the Indicated Mean Effective Pressure (IMEP)

$$IMEP = (Pn_r/V_dN)$$

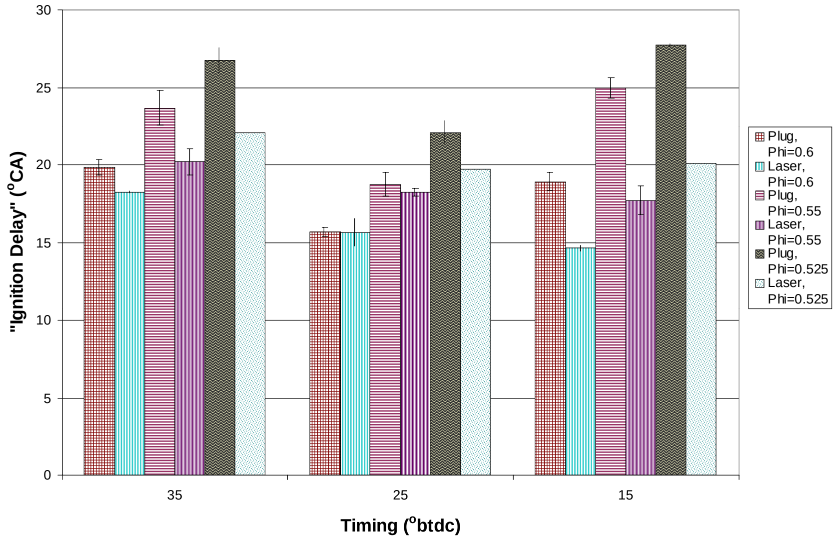


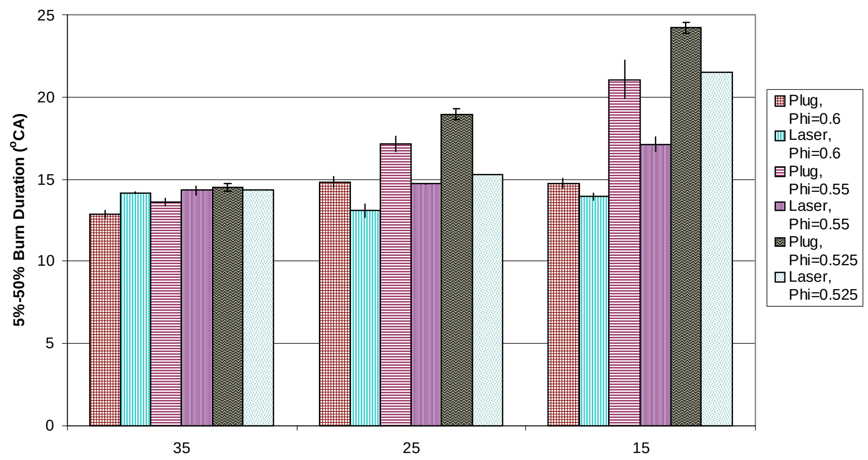
Thermal Efficiency

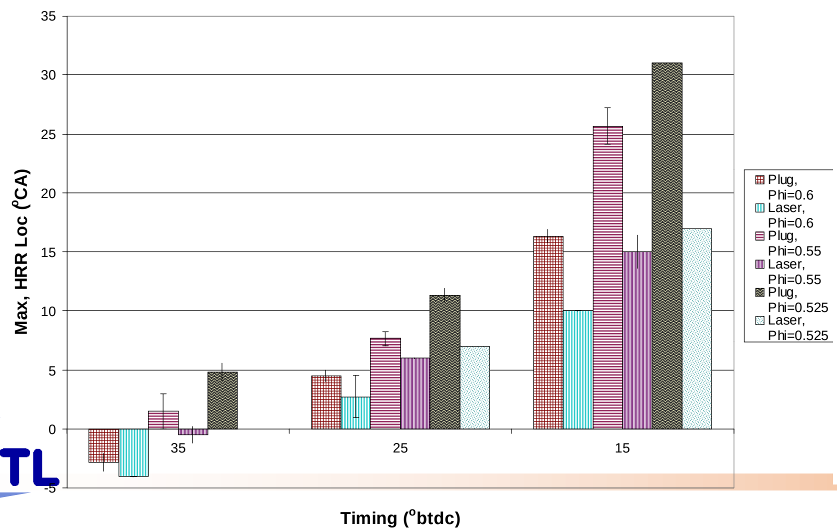
- Thermal Efficiency Factors
    - Combustion Efficiency
    - Phasing - (Example: Optimum timing at ϕ = 0.55 differs by 4ºCA)

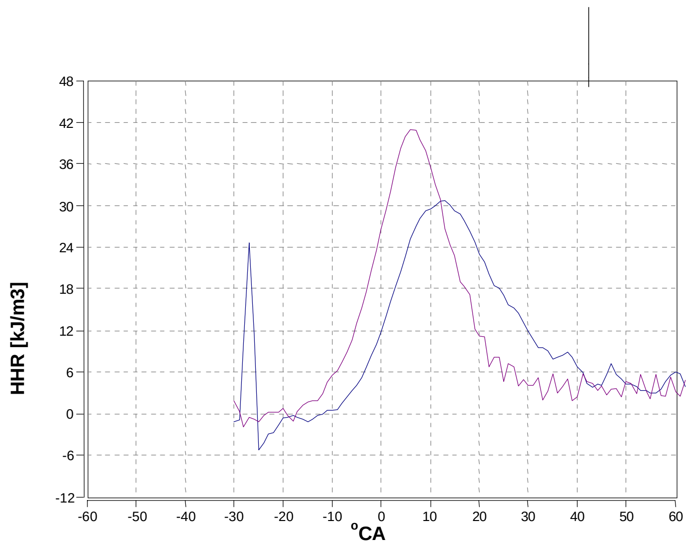


Ignition Delay, 5%-50% Burn Rate and Location of Maximum Heat Release Rate



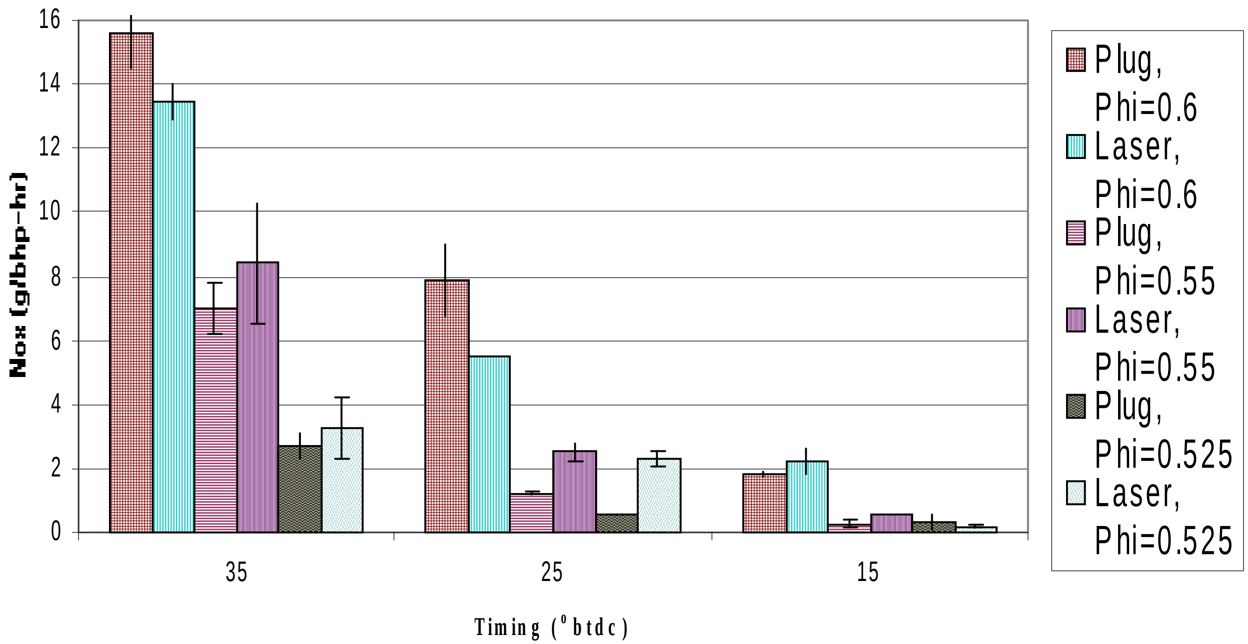




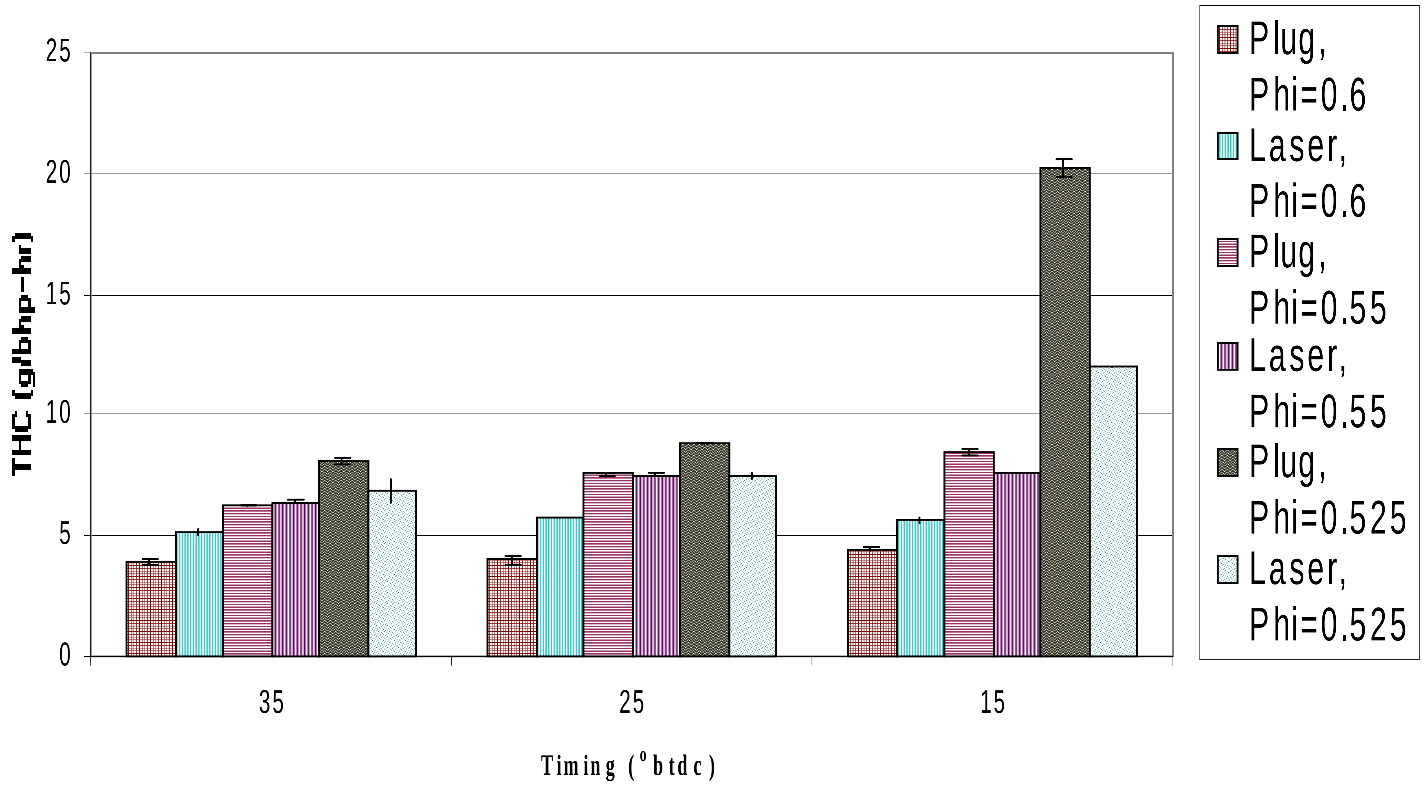


NOx vs Static Timing

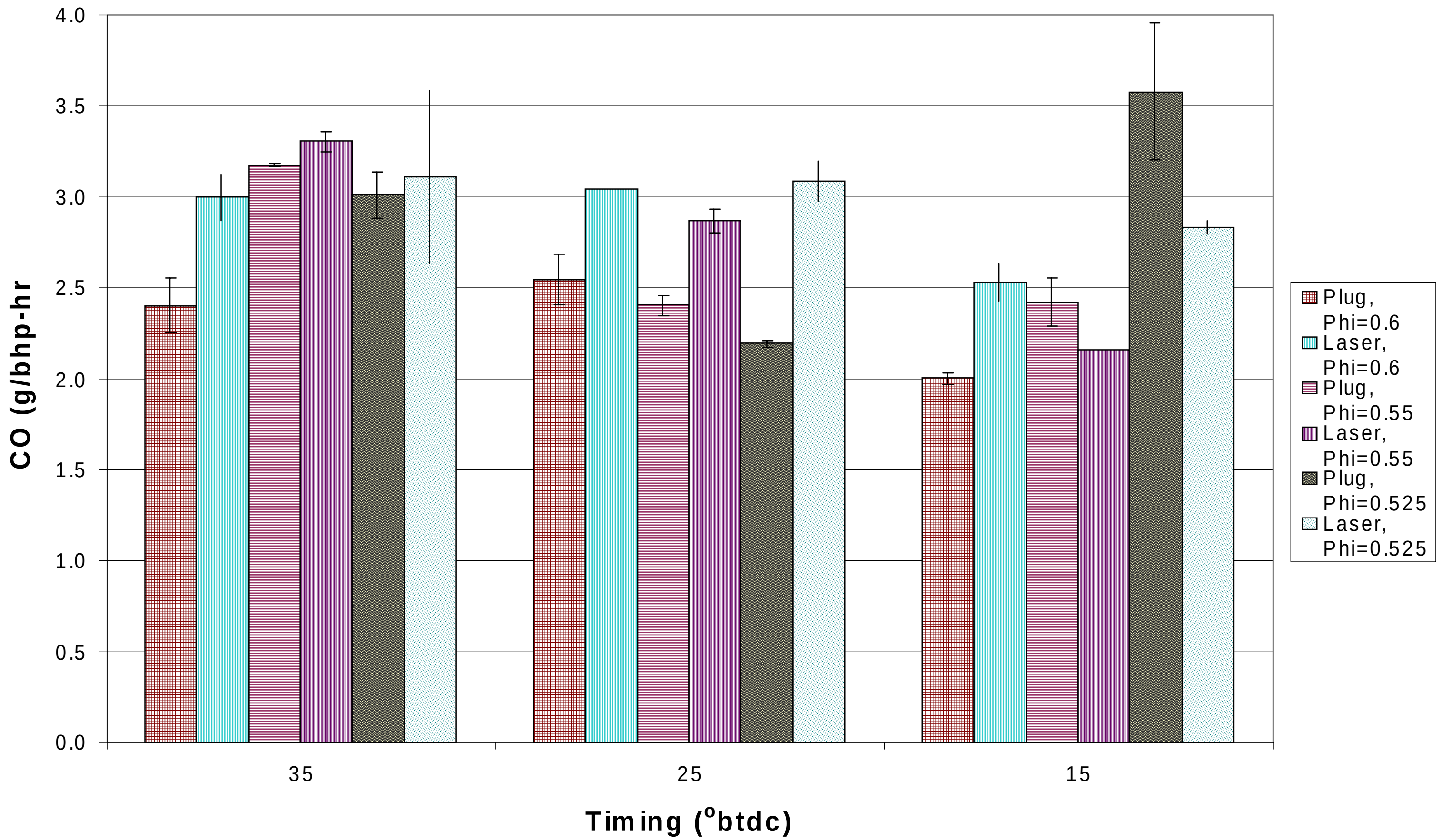
- •Phasing Effect
  - •Example: A 4ºCA spark retard (corresponding to Δ in T.E.) for the laser system from 35ºCA to 31ºCA reduces NOx form 8 to 4 g/hp-hr



THC vs Static Timing



CO vs Static Timing



Conclusions: Engine Testing to Date

- Significantly impr
lean equivalence r
spark system.
- Window fouling du
not apparent durin
operation.
- NOx emissions we
However timing op
- Hydrocarbon emis
the lower equivale
- Emissions of CO w
improvement in C
optimization.
- Laser spark opera
leaner than achiev

Laser	Equivalence Ratio = 0.5		
Timing (°btdc)	**35**	**25**	**15**
Torque (nm)	130.44	121.35	67.84
Therm eff. (%)	41.85	39.02	21.73
NO_x Rate (g/bhp-hr)	1.05	0.20	0.13
CO Rate (g/bhp-hr)	2.52	2.82	7.09
THC Rate (g/bhp-hr)	10.58	14.44	33.92
Pmax (bar)	39.11	28.69	21.08
Pmax Loc (°CA)	9.50	12.75	1.95
IMEP COV	1.31	3.72	18.25
5%-50% Burn Duration (°CA)	15.98	18.50	23.75
SOC (°CA)	-8.48	-1.75	8.23
Ignition Delay (°CA)	26.53	23.25	23.23
HRR Peak (KJ/M^3)	41.05	28.90	16.25
HRR Peak Loc (°CA)	5.00	12.00	21.00

Future Direction

- **Single point ignition with comparisons to correct phasing.**
  - Timing optimization (Phasing) vs. Thermal Efficiency
  - Look at NOx Trade off
  - Knock Margin
- **Multipoint laser ignition studies**
  - Higher apparent flame speed may provide additional knock margin as well as higher burn rate
- **Multipulse Ignition**
  - May provide improved ignition, leaner combustion and lower emissions
  - May provide a way to circumvent beam delivery issue
- **Distributed ignition**
  - May provide a way to circumvent beam delivery (energy density) issue

Collaboration Efforts

- **Laser-spark ignition Working Group**
  - Initial meeting on or about October 8-9, 2002
  - Organized by ANL (David Livengood)

The End……Thanks!

Technical Barriers/Solutions

Barriers

- *Laser Technology (Being Evaluated)*
- *Optics*
- *Particulate Deposition*
- *Focal Length Effects*

Potential Solutions

- *Distributed System*
- *Improved Fiber Optics for beam delivery, quality optics*
- *Multi-pulse Mode*