Laser Spark Ignition for Advanced Reciprocating Engines

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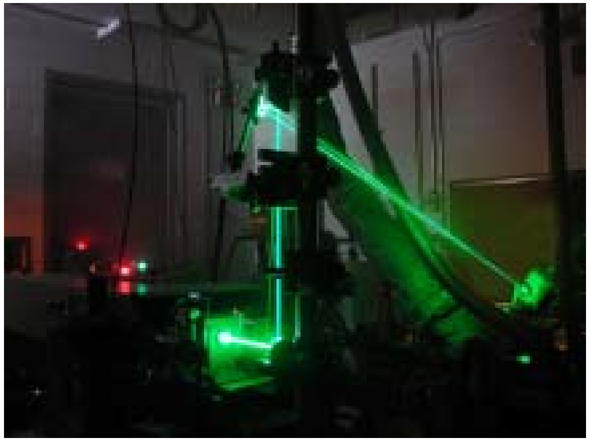
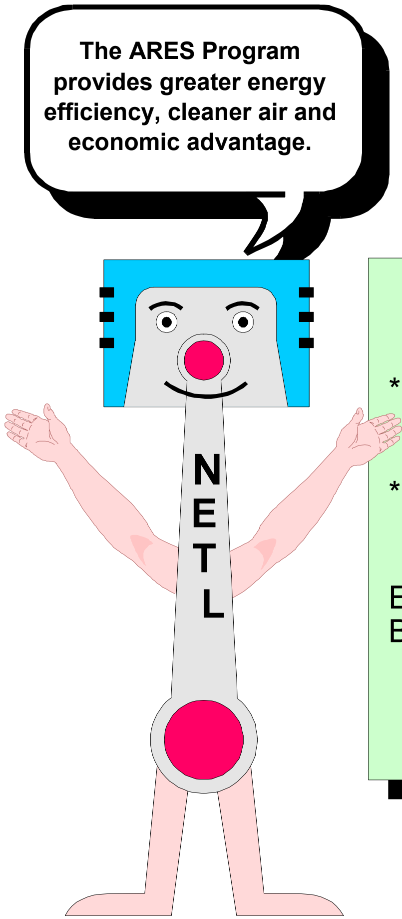


December 3, 2003

2003 Distributed Energy Peer Review

ARES Overview: Program Benefits



Benefits

	Improvement		Outcome
	From	To	
*Efficiency	38%	50%	- Savings of $320M/yr in fuel cost - Reduction of 8-12M tons/yr CO_2
*Emissions NOx	1 g/bp-hp →	0.05 g/bp-hp	- Reduction of 40,000 - 60,000 tons/yr NOx
Economic Benefits	Will provide domestic engine manufacturers the leverage to compete against foreign manufacturers in this the expanding U.S. Distributed Generation and World		

* Assumes 25% market penetration in 300-3000kW range in current NG receprocating Engine Market

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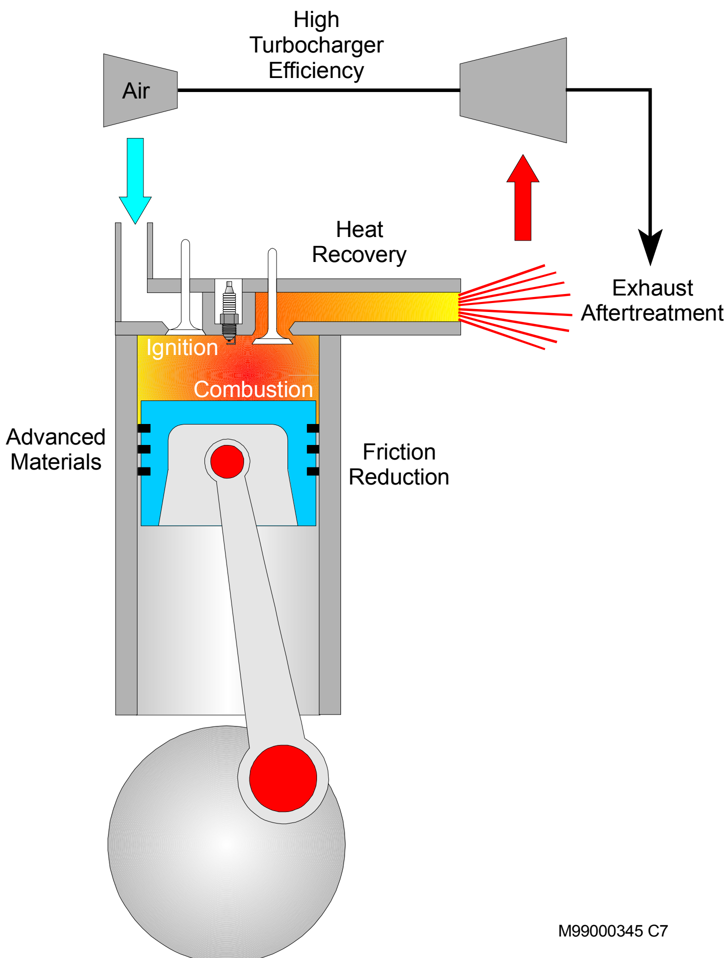
ARES Overview: Technology Requirements



✓**Ignition** targets the issues with spark plug wear and lean-burn combustion limits in natural gas engines.

✓Advanced **Combustion** methods are needed to achieve the target low NOx emission and high efficiency levels and <u>especially a widened knock margin</u>. Focused efforts are needed on computer modeling and simulation of advanced concepts.

✓**Advanced Materials** are projected to be an important element of the ARES program for applications in demanding high-temperature designs and components.

✓**Advanced Sensors and Controls** will be needed as part of a next-generation system for engine controls to meet the aggressive emissions and efficiency targets. New exhaust emission sensors for NOx, in-cylinder pressure measurement, dynamic torque sensors, advanced engine diagnostic strategies are examples of key components.

✓**Exhaust Aftertreatment** is a key element of achieving the low emission targets. Development of specific catalysts for these engines will be one of the most significant challenges. Spin off technologies will benefit other stationary and mobile applications.

✓**Heat Recovery and Friction Reduction** have shown to be two very important issues from recent engine modeling by Southwest Research Institute and the ARES Engine Consortium. Novel coatings that reduce ring pack friction and reduce heat transfer to engine liner and piston will be investigated.

Goal and Objective

- **Develop scientific and engineering foundation for commercial laser spark ignition in reciprocating engines**
  - Why do we need a new ignition technique?
    - A durable high performance spark ignition system is a barrier technology for development of engines with low emissions and simple-cycle efficiency exceeding approximately 45%.
    - The DOE’s goal is 50% simple cycle electrical efficiency with less than 0.1 g/bhp-hr NO_x emissions for stationary natural gas fueled engines.

Introduction: *Why Laser Ignition?*

- **Potential for Improved Durability**
  - 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
  - In Ultra-lean, high BMEP natural gas engines, Spark Plug Service Life Is Very Low due to Increased Ignition Coil Energy Requirement
  - Rugged, low cost lasers are available for numerous industrial processes, which used as an ignition source, offer the potential for extended service life
- **Potential for Improved Engine Performance**
  - Robust spark breakdown has shown greater ignitability, potential for misfire limit extension and low emissions
  - Further performance improvements (multipoint ignition, decreased real estate, bigger valves, this technology may enable other “tricks”)

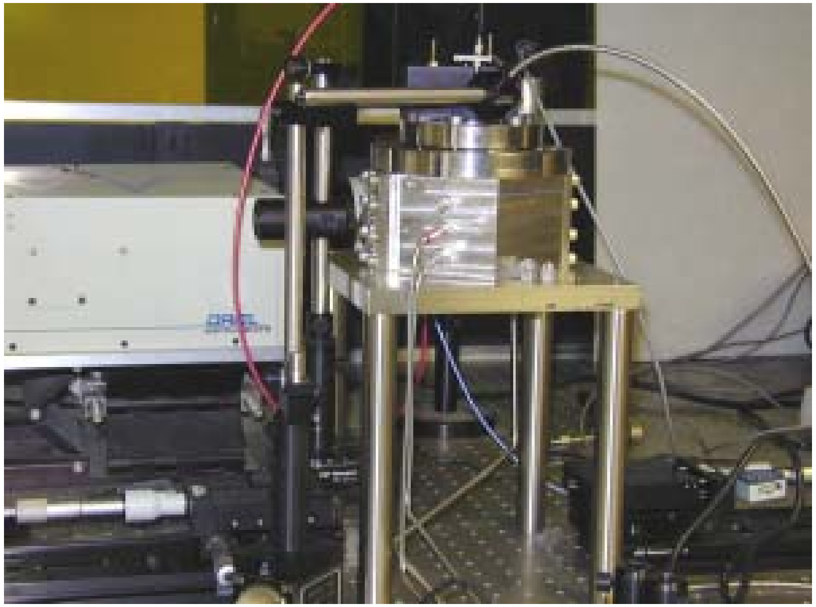
TECHNOLOGY STATUS

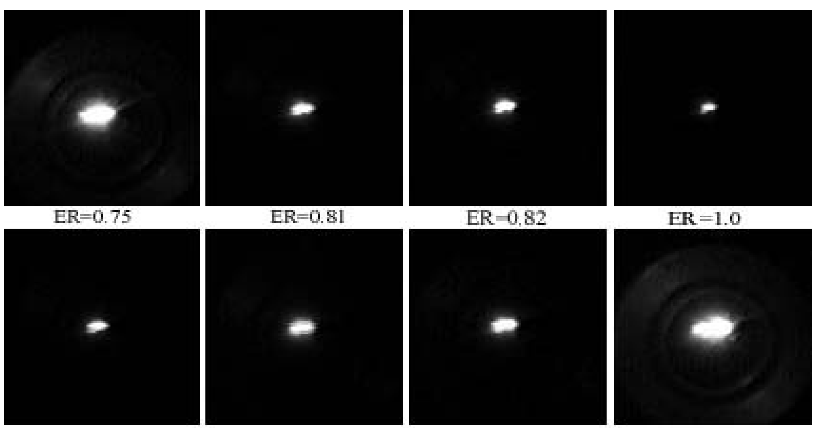
- Previous engine work was focused on laser ignition of gasoline (Dale, et al., 1979) , or propane (Smith, 1979).
  - **Recent lab scale work has demonstrated increased flame speed and combustion pressure over conventional spark systems (Tran and others).**
  - **Current work at NETL, ANL, SWRI, CSU.**
  - **Big investment in Europe by Jenbacher.**
- Mass production of lasers at significantly reduced size and cost is imminent
- However, delivery of high peak power laser energy is problematic
  - **50 mJ, 5 ns Nd:YAG pulse in a 1mm dia. Optical fiber produces 1.27 GW/cm^2**
  - **Current damage threshold is somewhere around 0.5 to 3gw/cm2 for short duration. Divergence effects further limits fiber size to approx. 0.1mm (127 GW/cm^2)!!!**

Work Summary

- **Fundamental Studies**
- 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

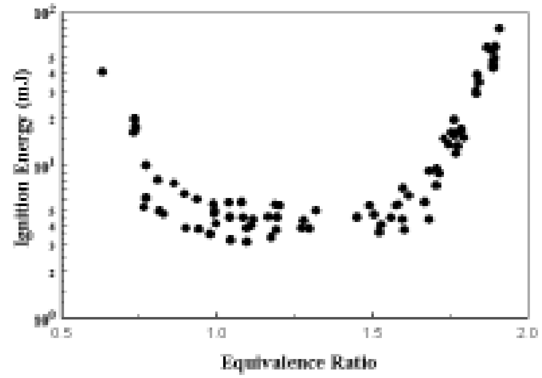
Fundamental Laser Ignition Lab

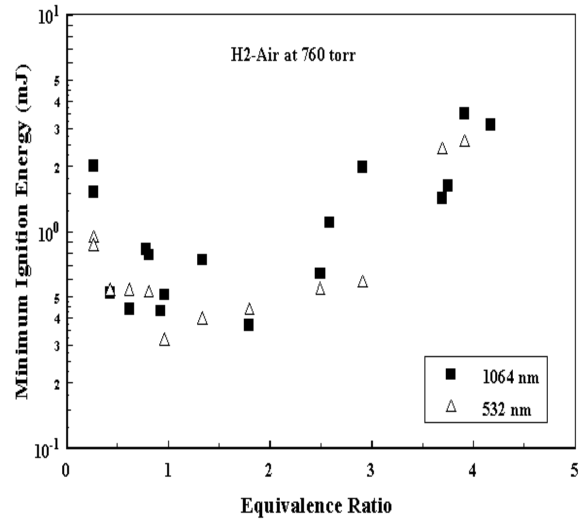




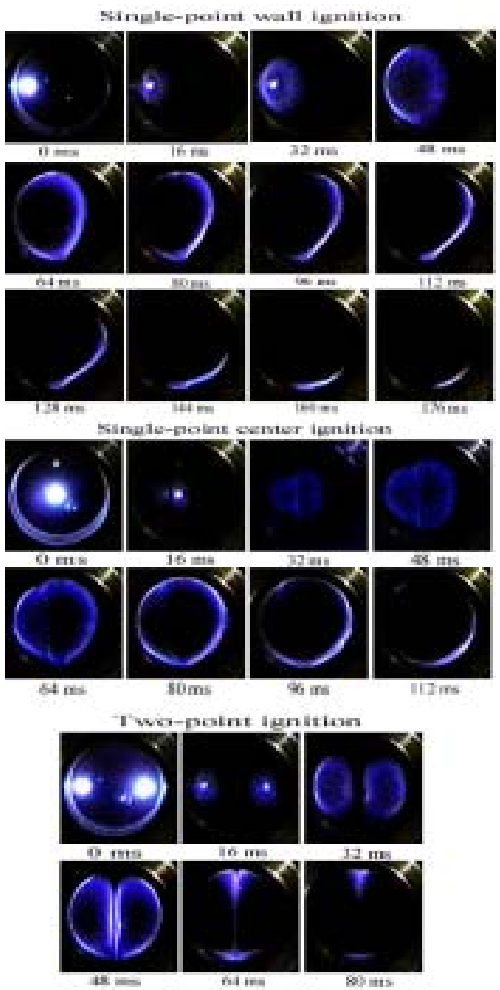
ER=0.75 ER=0.81 ER=0.82 ER=1.0

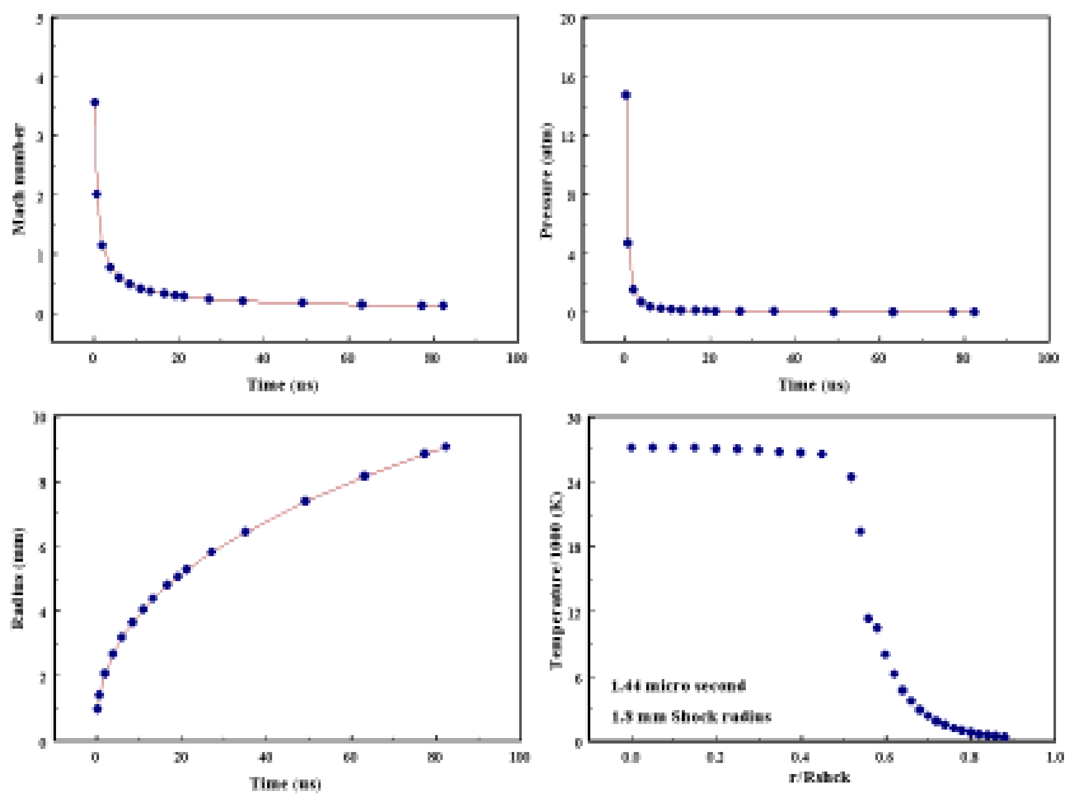
ER=1.36 ER=1.59 ER=1.81 ER=1.95



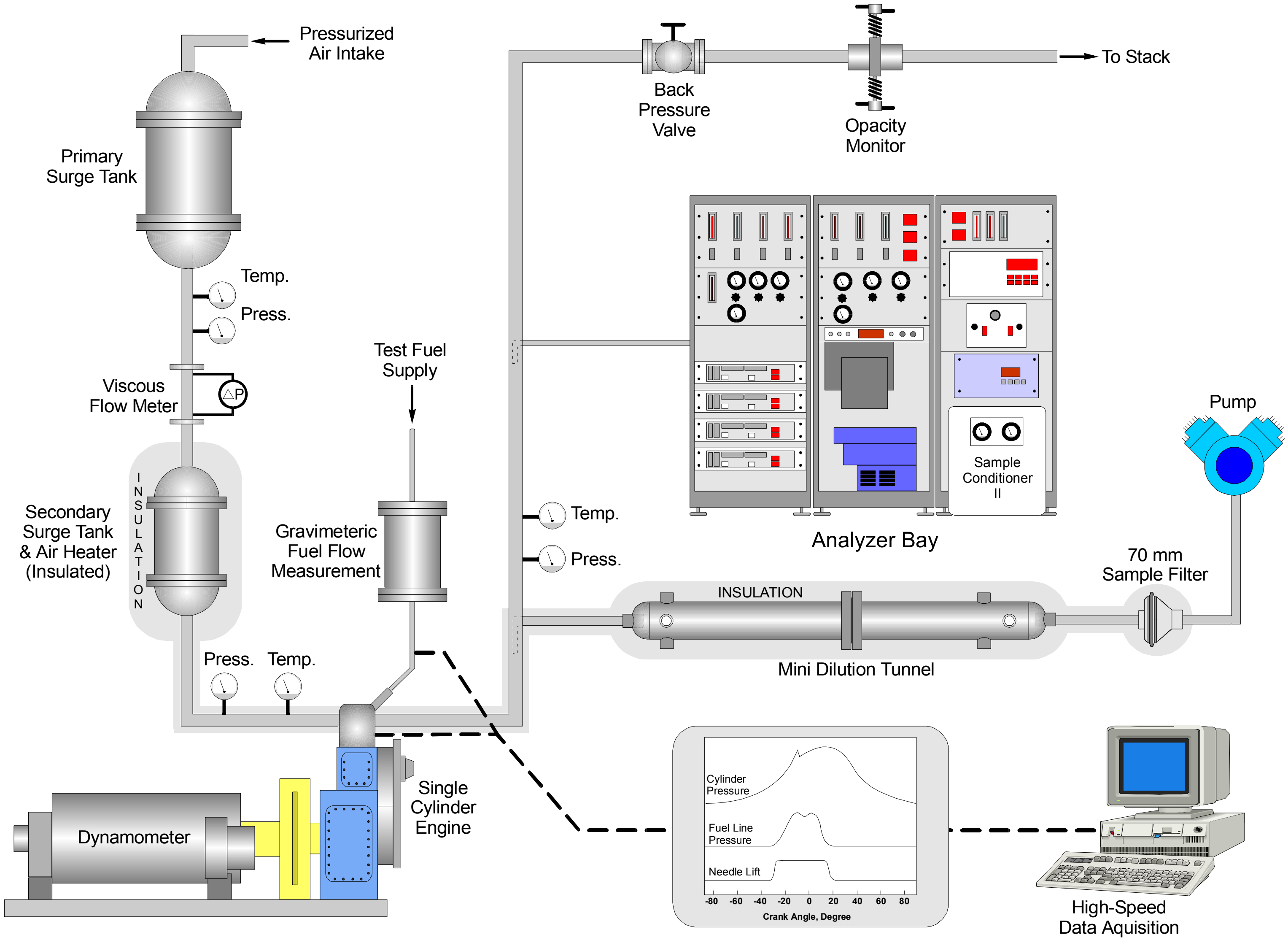


Fundamental Laser Ignition Lab (cont.)





Engine Testbed Schematic



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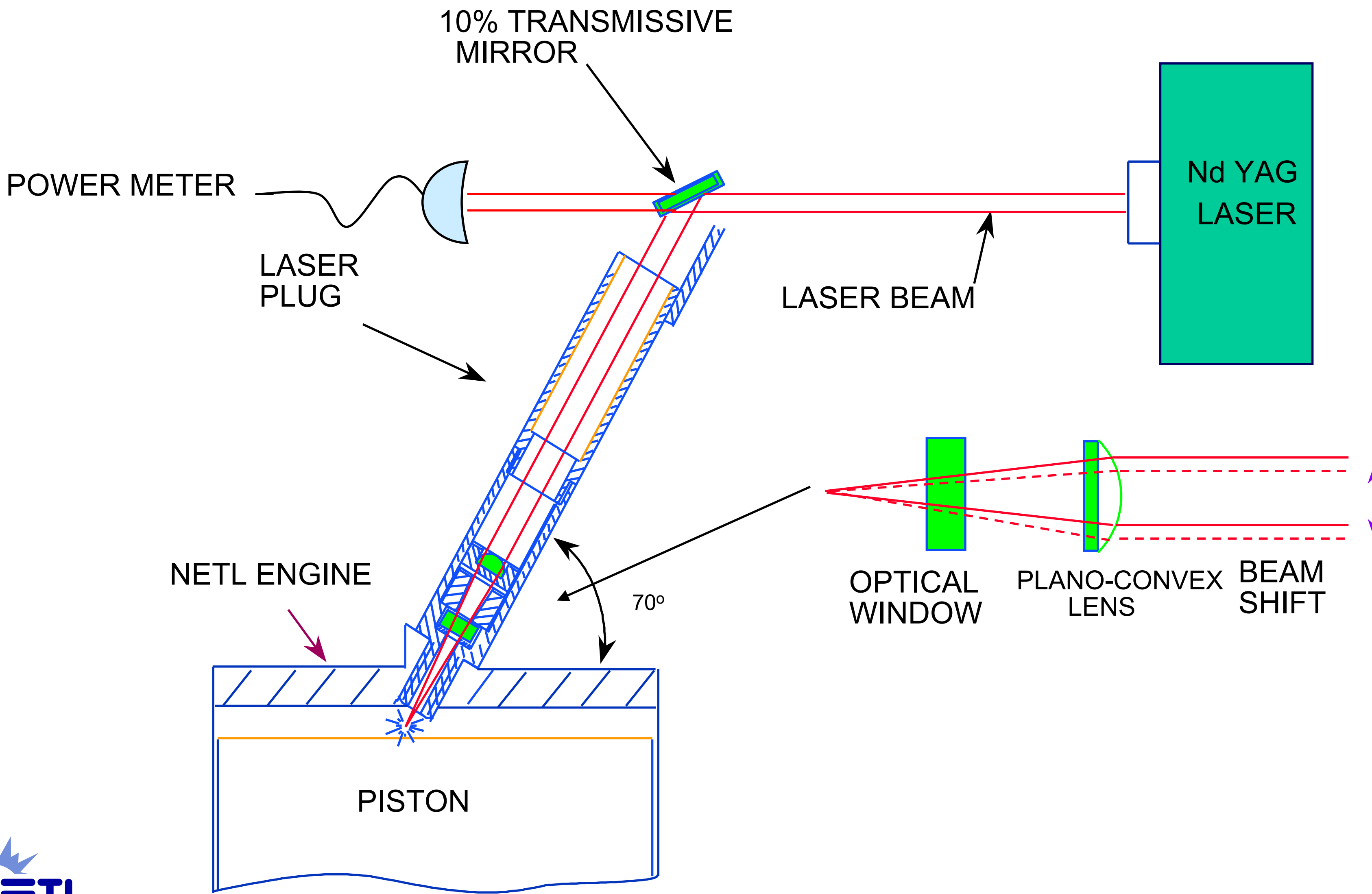
Laser Arrangement (Temporary)



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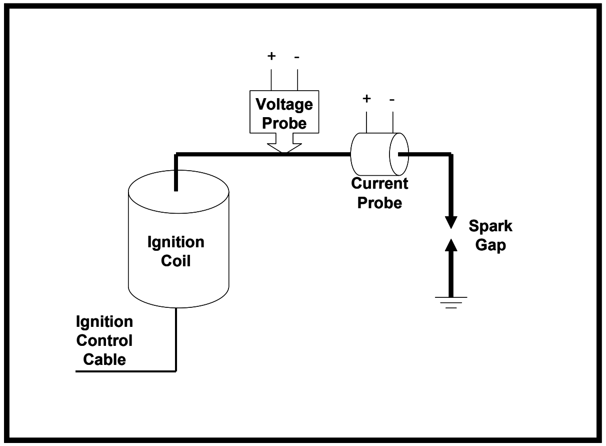
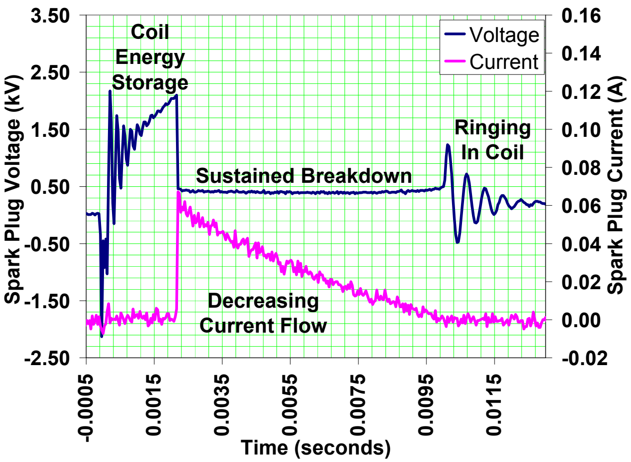
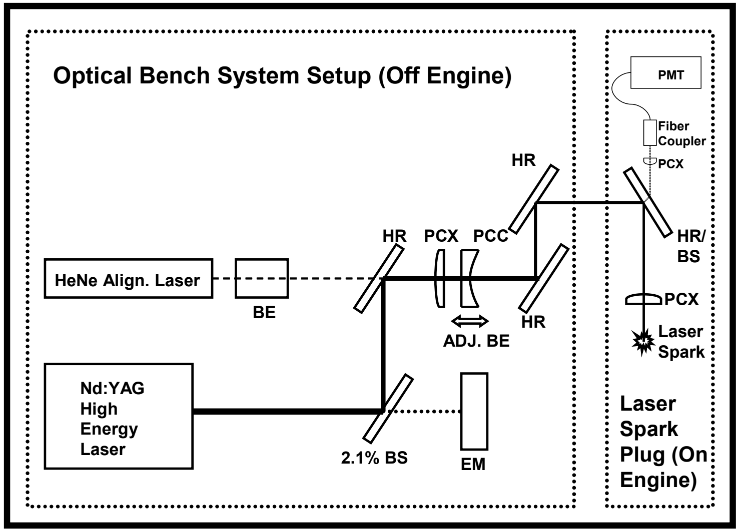
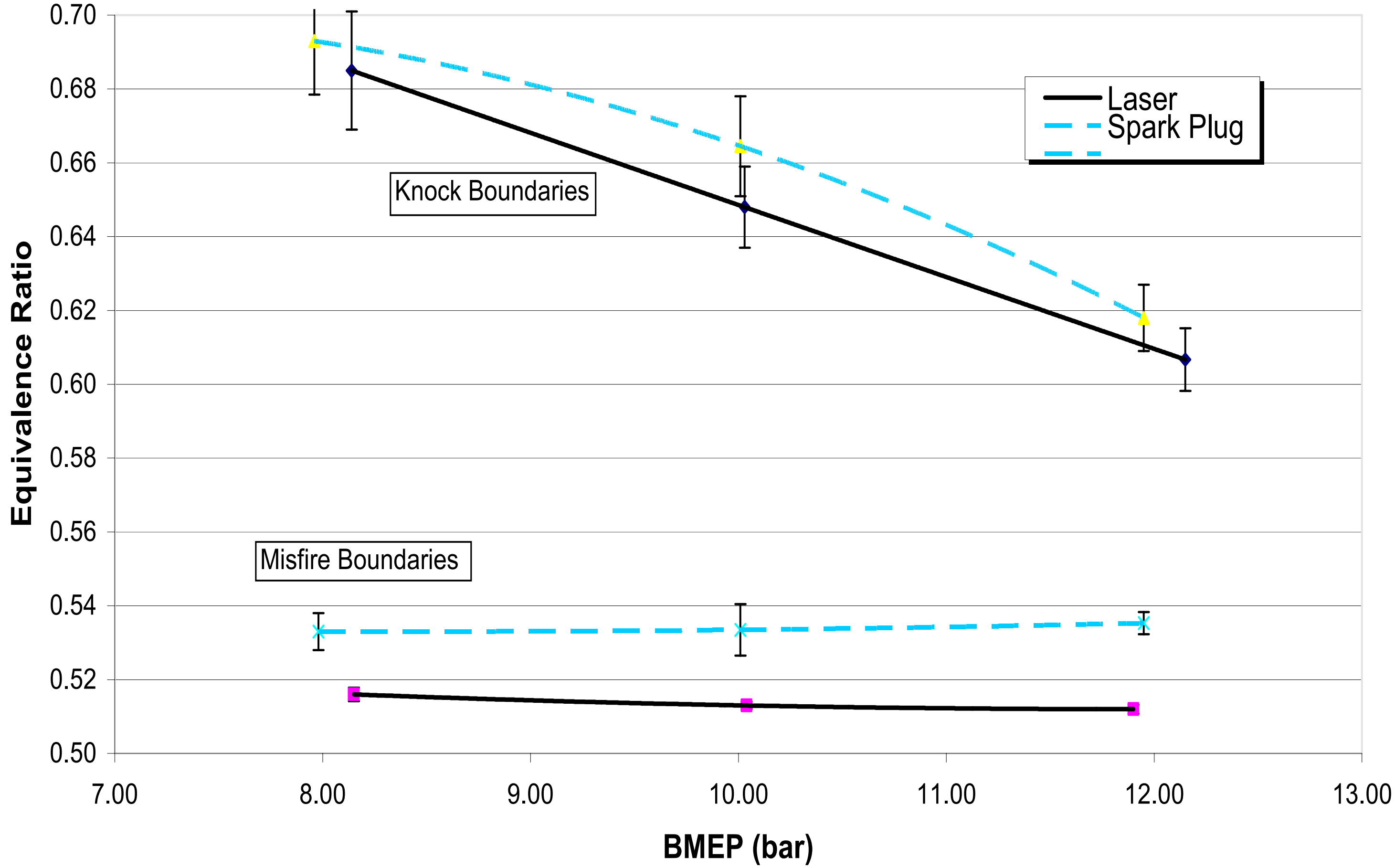
A Few Details



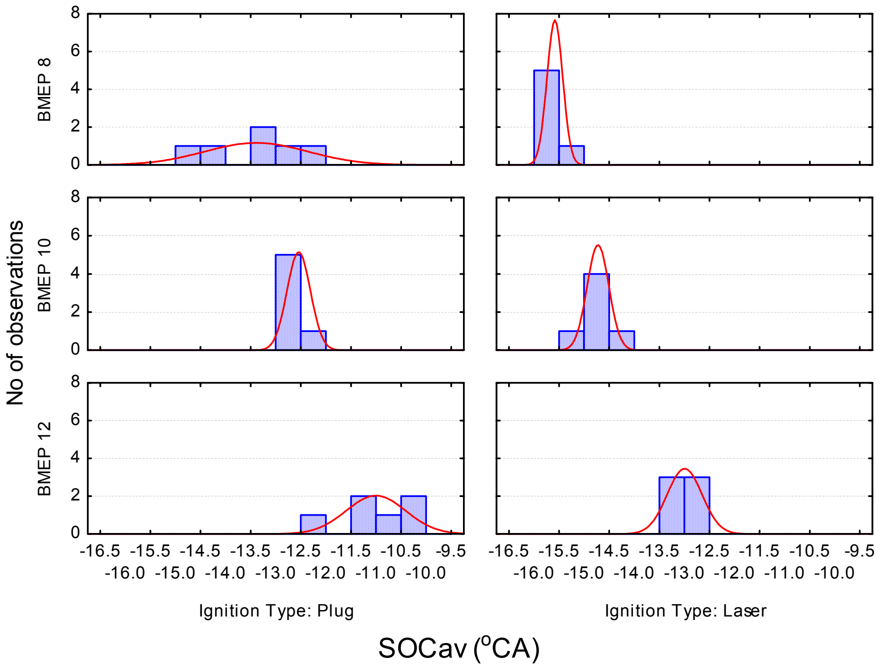


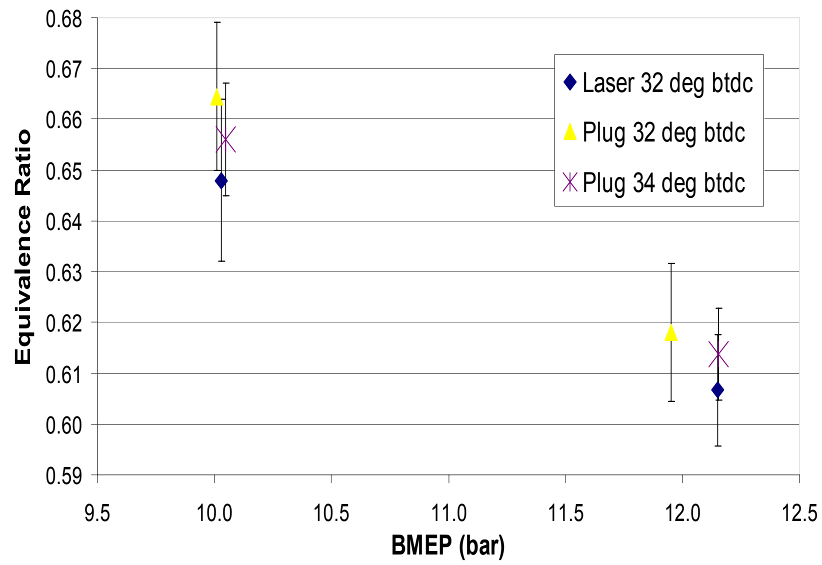


Knock and Misfire Boundaries (32^{o}btdc constant timing, 10% IMEP COV)

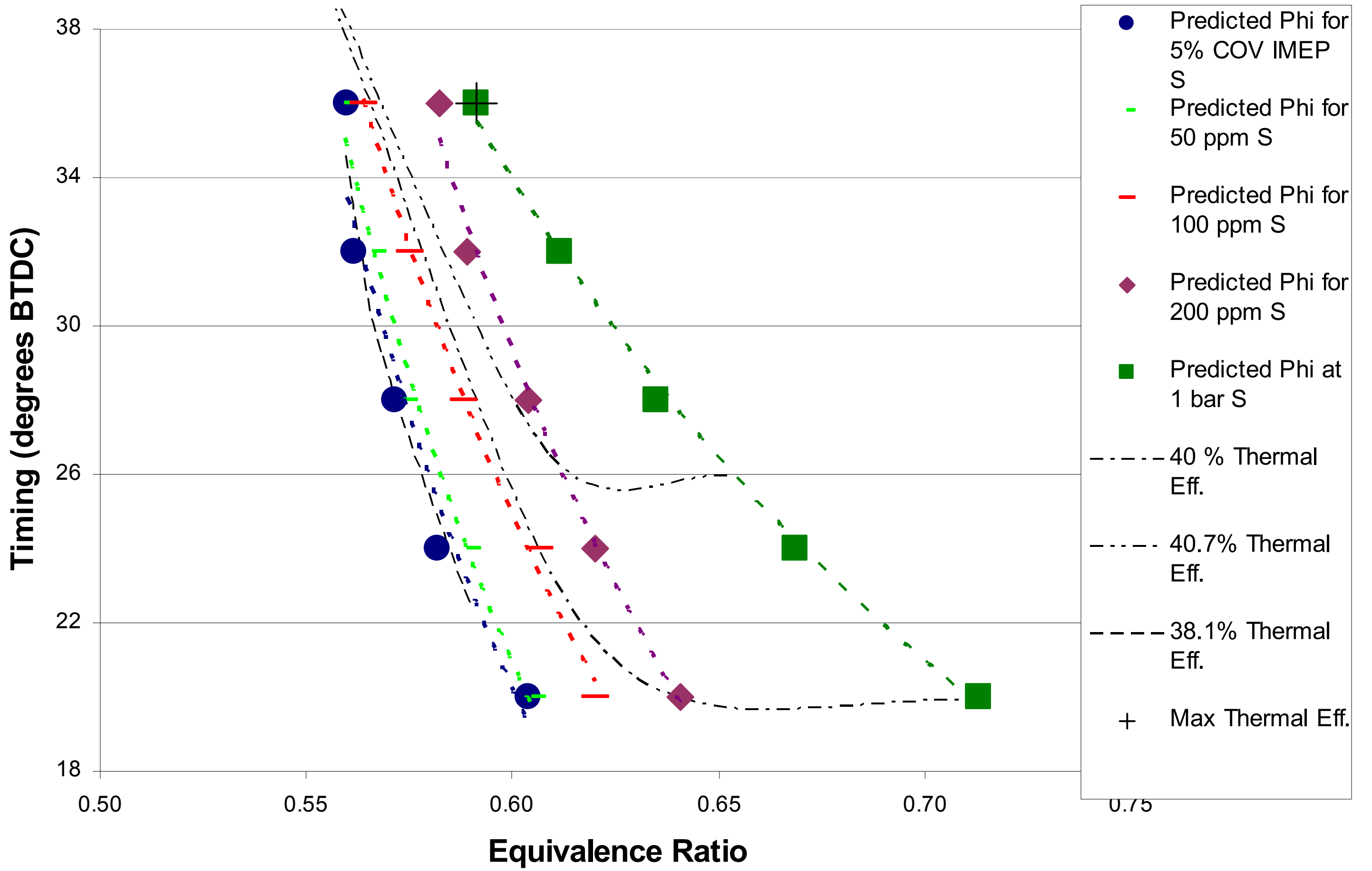


Knock Boundary Affected by Ignition Delay

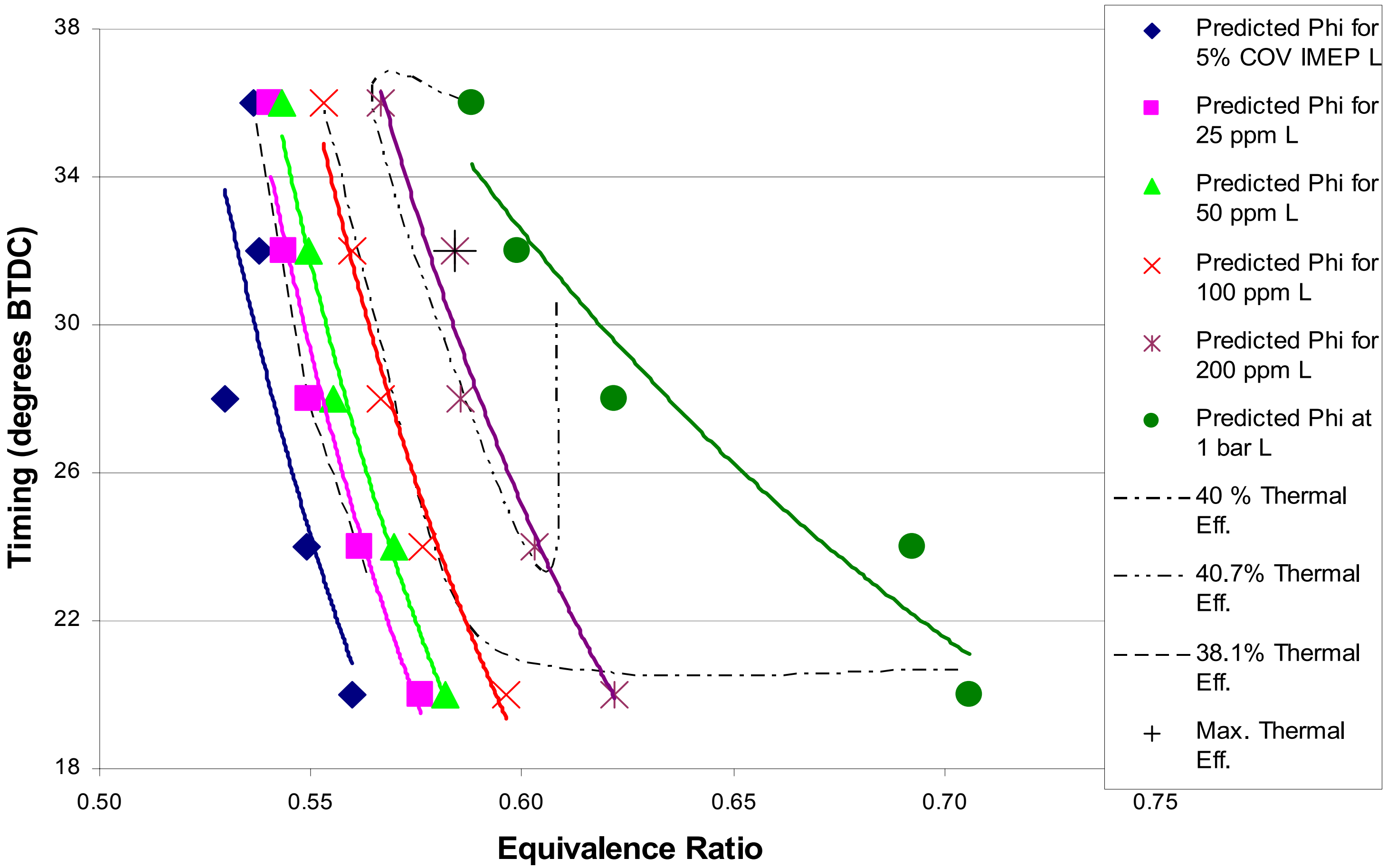




Conventional Spark: Lines of Constant NOx and Thermal Efficiency



Laser Spark: Lines of Constant NOx and Thermal Efficiency



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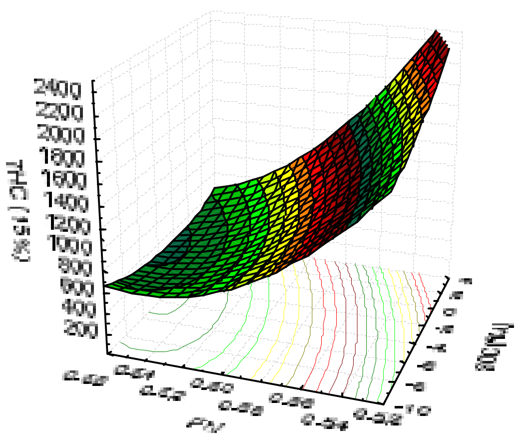
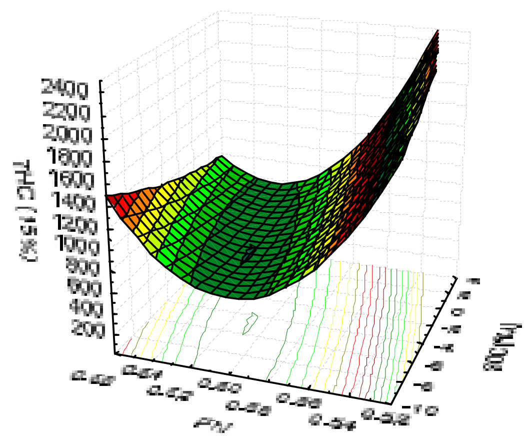
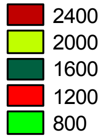
THC Emissions



Run Descrip: Spark Plug



Run Descrip: Laser



Conclusions

- **Optical and spectroscopic data have revealed and/or validated that:**
  - The ignition process seems to be dominated by the **hot ball of gas** remaining after the laser spark has dissipated.
  - **Multipoint ignition** via laser delivery offers potential for engine applications to further extend misfire and knock limits.
  - Ignition energies well less than 50mJ/pulse are may be sufficient for laser spark (50mJ/pulse represents a level in which energy effects “flatten”)

Conclusions (cont.)

Engine Testing to date has indicated:

- **Window fouling** was not apparent although longer duration testing is required to verify this observation
- The **misfire limit** is shown to be significantly extended for laser ignition. (approximately 0.535 to 0.513 with laser ignition assuming misfire limit at an IMEP COV of 10%)
- **Ignition delay** was approximately 7% shorter for laser ignition resulting in a 2^{o}CA advance in SOC
- **Burn duration** was slightly longer for laser spark combustion.
- Significant **extension of the operating window** thus providing **lower NOx** emissions at equivalent levels of hydrocarbon emissions and thermal efficiency.

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Future Direction

- **Basic combustion/ignition studies**
  - Burn rate limited or ignition limited?
  - What are performance limits?
- **Multipoint laser ignition studies**
  - Higher apparent flame speed may provide additional knock margin as well as improved ignitability. Higher apparent burn rate.
- **Prototype Laser Ignition System Development (CP)**
  - Multi-pulse 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
  - In progress (will be reported on next time including engine testing of key prototypes)
- **Multi-cylinder Engine testing (CP)**

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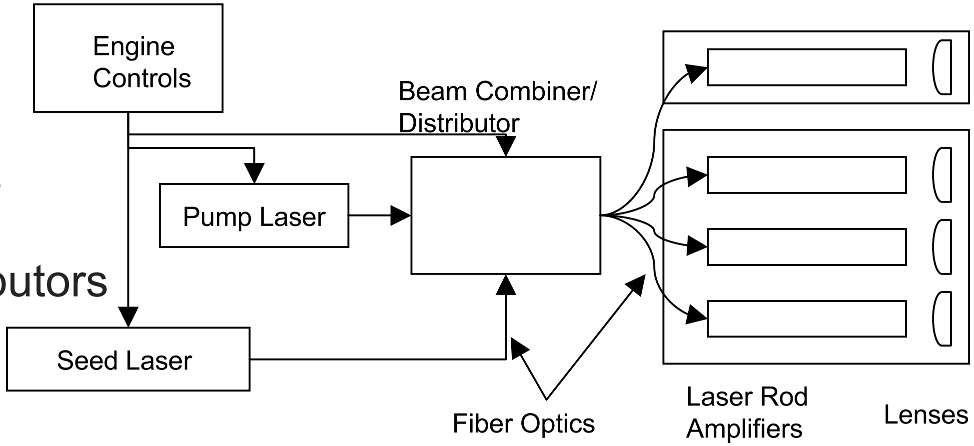
Work Plan Summary

- **Engine Performance Testing for Laser Ignition Systems**
  – Single Point Testing
  – Optical Engine Testing
  – Multipoint Testing
- **Laser System Development**
  – Optical Fiber Coupling
  – Optical and Electrical Distributors
  – Optical Access
  – Design and Packaging
  – Prototype Evaluation
- **Multi-cylinder Engine Demonstration Testing**
- **Advanced Concepts**
  – Fiber Optic Delivery of High Peak Power
  – Misfire limit extension
  – Reducing Breakdown Intensity
  – Laser ignition applications to HCCI
  – Spectroscopic A/F Diagnostic Development
  – Flame Kernel/Spark Interaction Spectroscopy
  – Engine Testing of Advanced Concepts



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