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CROSS-CUTTING TECHNOLOGIES TO ENABLE CLEAN ENERGY MANUFACTURING

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CONNECTION TO AMO MISSION

Distributed Generation (DG) systems improve energy efficiency, carbon footprint, reduce emissions, and facilitate market opportunities enabling U.S. manufacturers to be cost-competitive and energy independent.

Opportunity

Performance improvements in DG are limited by Ignition which could impact several Giga-watts of electricity generation (10,000 deployed in US)

Applications

- Distributed Generation
- Combined Heat and Power
- Mining
- Oil & Gas
- Solar/wind power firming

Prime Mover Features:

- Engine Size: 0.5-20 MW (large bore)
- Fuel: Natural Gas and other opportunity fuels

6-CYL NATURAL GAS ENGINE OPERATION IGNITED BY μLASERS

Publication:
Sreenath Gupta, Bipin Bihari, Muni Biruduganti, Qing Wang, Robert Van Leeuwen, “Performance Benefits of Laser Ignition in a Natural Gas 6-cylinder Engine,” Laser Ignition Conference 2016, Yokohama, Japan, May 2016.

PRINCETON OPTRONICS

Argonne NATIONAL LABORATORY

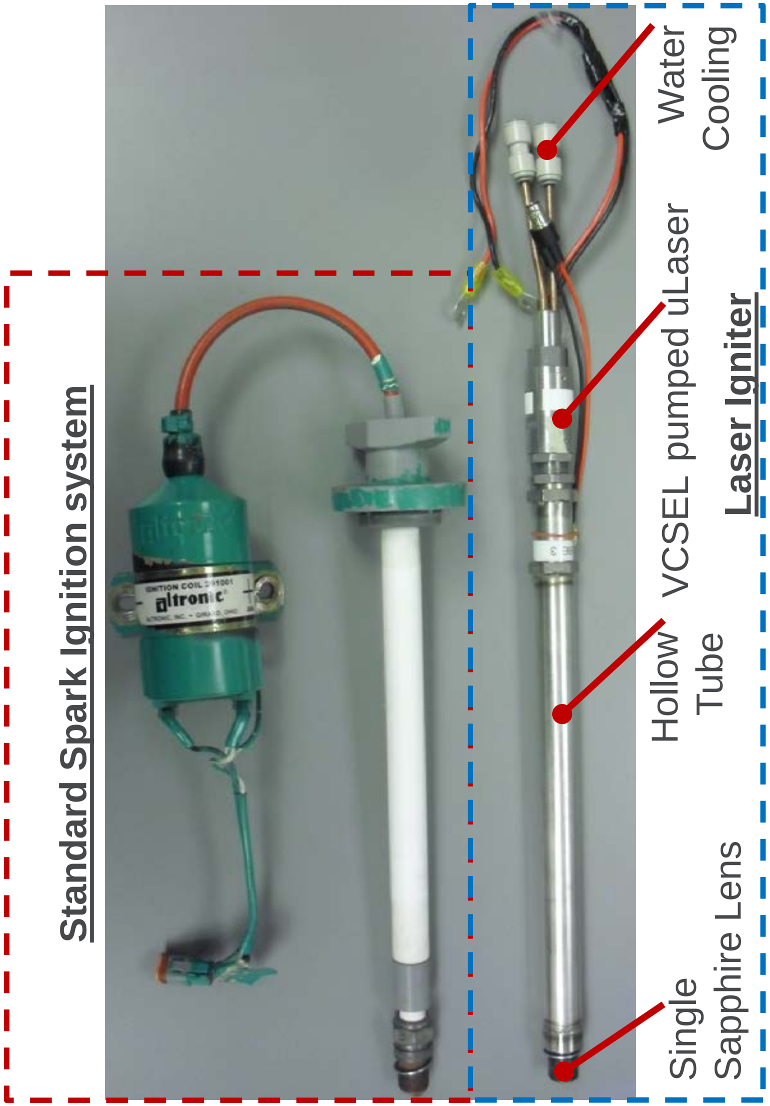
LASER IGNITION OFFERS IMPROVED PERFORMANCE OVER SPARK IGNITION

Advantages

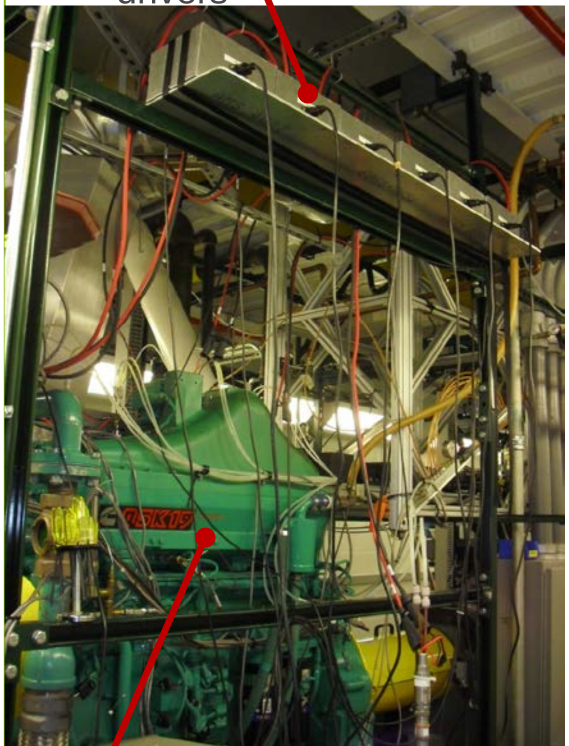
- Improved ignition stability
- Extension of lean ignition limits
- Combustion with higher EGR

Customization is possible

- Higher laser power
  - Flame acceleration
  - Lean burn/ EGR extension
- Multi spark
  - Improved ignition stability
- Multi point
  - Faster combustion
- Optimal spark placement



Laser Diode drivers



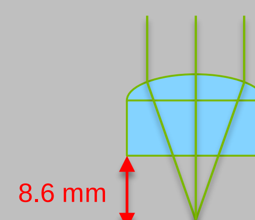
350 kW, Inline 6-cylinder, turbocharged, Cummins natural gas engine coupled to 463 kW AC Dynamometer

Standard SI as seen from cyl-1 end of the engine

Installed uLaser igniters as seen from cyl-1 end of the engine

Laser

- Single-pulse, two-pulse
- Back Focal Length = 8.6 mm
- 1064 nm, 15 mJ/p, 5 ns FWHM

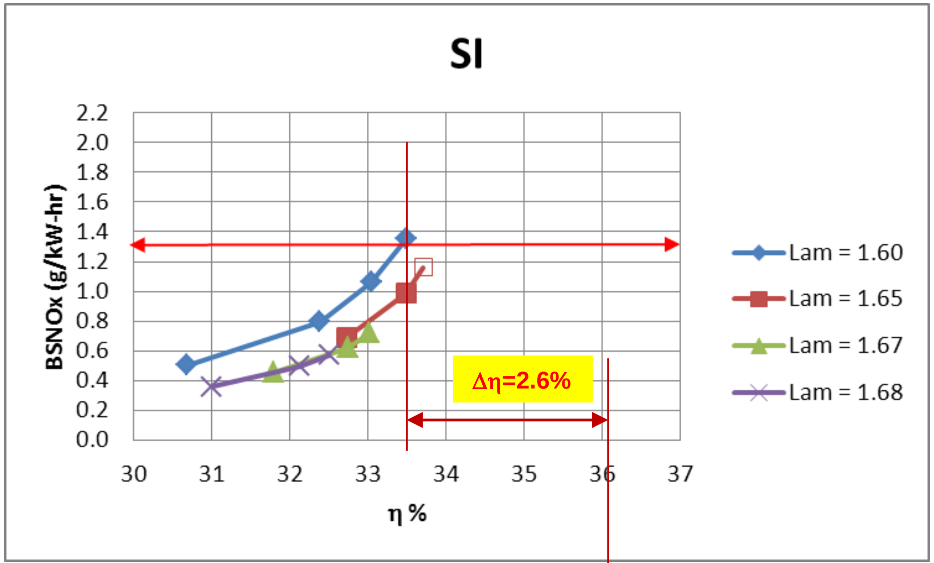


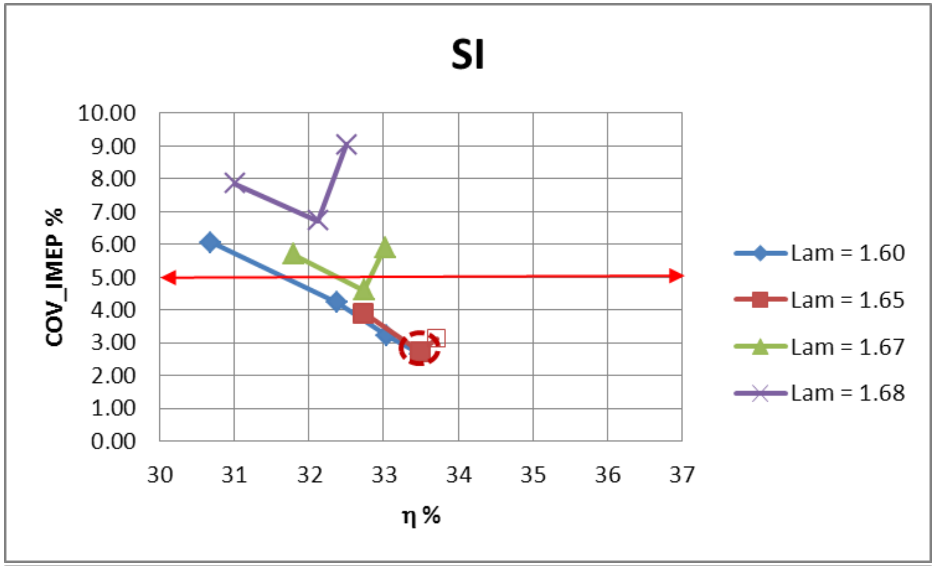
Engine

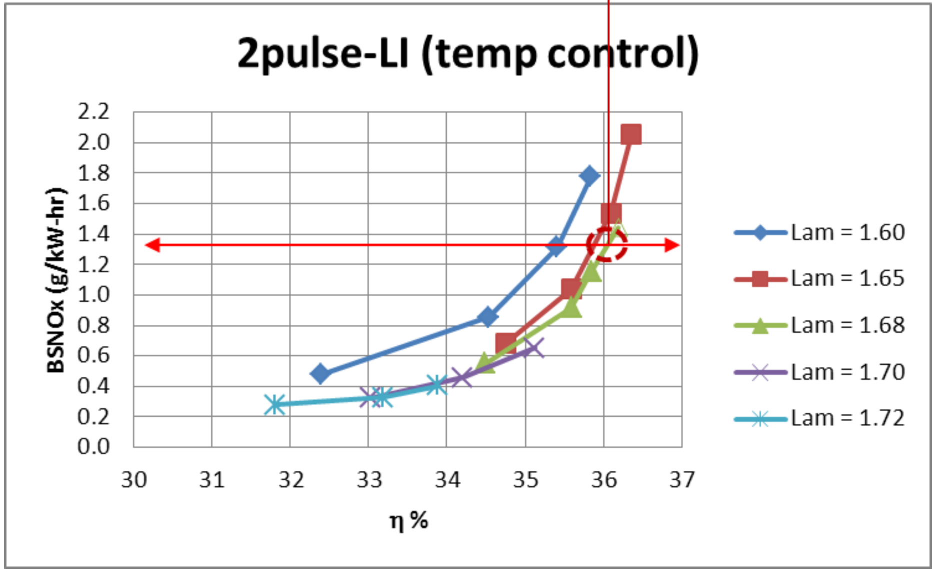
1800 rpm, 298 kW

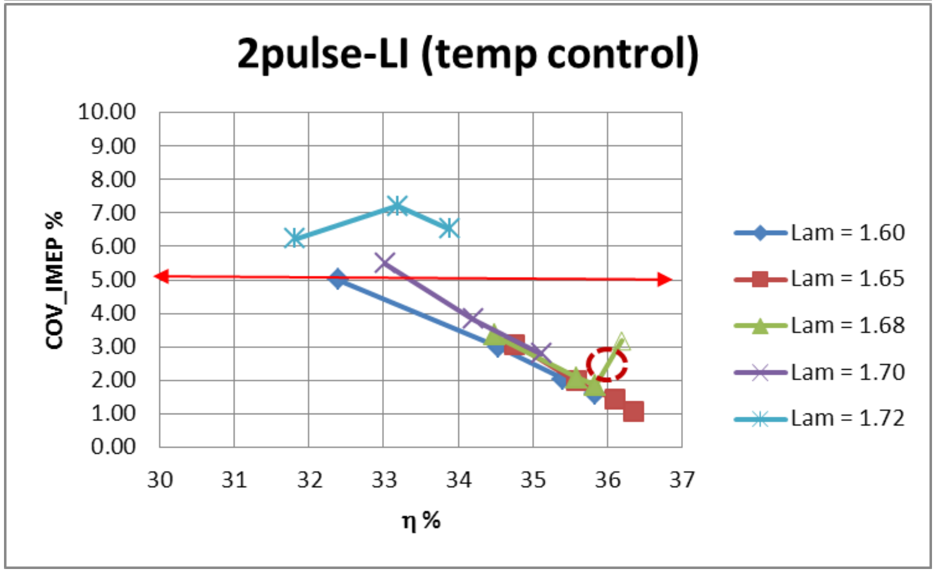
Constraints

- $BSNO_x$ < 1.34 g/kW-hr (EPA regulation)
- COV_IMEP < 5% (Industry standard)









* Two-pulse LI with tighter temperature control offered the maximum benefit

SUMMARY

Major Findings

- A 6-cylinder natural gas engine was operated with microlaser igniters installed in all 6 cylinders *(a world's first demonstration)*
- Optimization of excess-air-ratio and ignition timing yielded efficiency improvement ($\Delta\eta$ = 2.6%) while meeting emission regulations and industry accepted ignition stability standards
- Efficiency improvement results with LI due to

ignition timing advancement + lean-burn operation

Impact

- Performance improvement due to LI could result in
  - $21.4k/yr/MW annual fuel savings to engine operator
  - Avoids 442 metric Tons of CO_2 emissions/yr/MW

Future Efforts

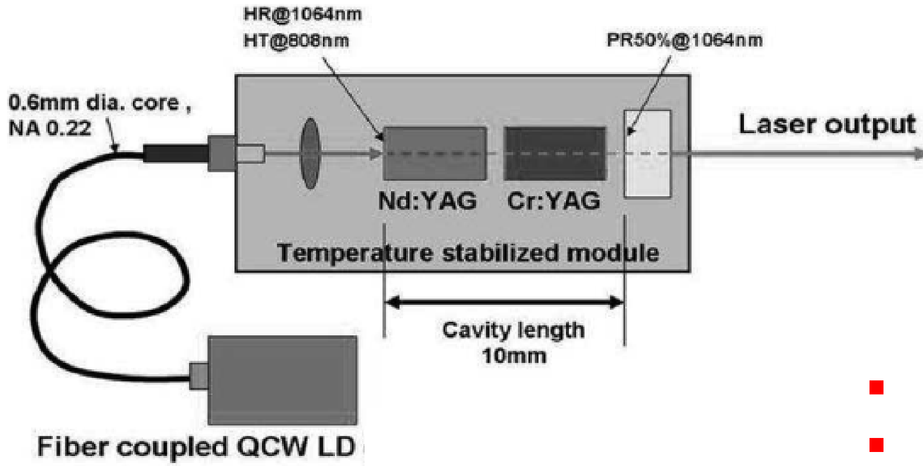
- High brightness laser with 3X laser power (a recent breakthrough) for further performance improvement
- Lens fouling mitigation for long-term durability will be investigated through a combination of various strategies

OPPORTUNITY = (PRECHAMBER IGN. + LASER IGN.)

Laser ign. → lean-burn combustion
Prechamber Ign. → faster in-cylinder combustion

Publication:
Sreenath Gupta, Bipin Bihari, Muni Biruduganti, Nicholas Polcyn, Jeong Ung Hwang, Kenji Kanehara, "Performance of SI and LI Spark Plugs and That of Spark Plugs Equipped With a Prechamber," Laser Ignition Conference 2016, Yokohama, Japan, May 2016.

DENSO SHARED THEIR 2-PART MICROLASER WITH ARGONNE FOR TESTING



DENSO

- 1064 nm;
- 0.9 ns (FWHM);
- 2.5 mJ/p; up to 11 pulses; 80 μsec apart

Pump laser

Nd:YAG laser

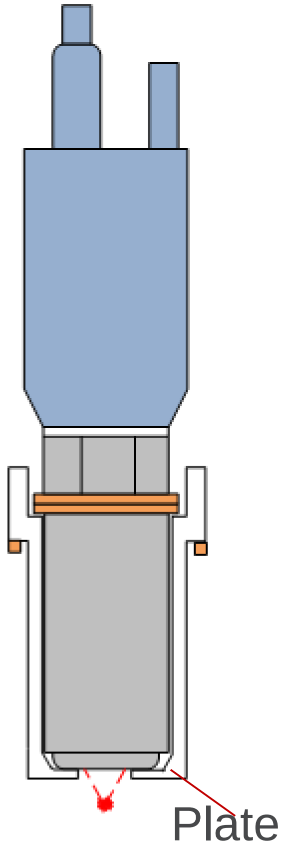
Masaki Tusnekane, Takayuki Inohara, Akihiro Ando, Naoki Kido, Kenji Kanehara and Takunori Taira, "High Peak Power, Passively Q-switched Microlaser for Ignition of Engines," IEEE journal of Quantum Electronics, Vol. 46, No. 2, pp. 277-284, Feb. 2010.

A NATURAL GAS SINGLE-CYLINDER ENGINE WAS USED AS IGNITION TESTBED

Engine Specifications	Single-Cylinder,4-Stroke,SI
Bore (mm)	130
Stroke (mm)	140
Comp. Ratio	11:1
Displacement (L)	1.857
Power (kW/hp)	33/45
Speed (rpm)	1800
Ignition System	CDI (Altronic Inc.)/ laser ign.
Lube oil	Idemitsu NPNA
Dynamometer	150 hp AC drive

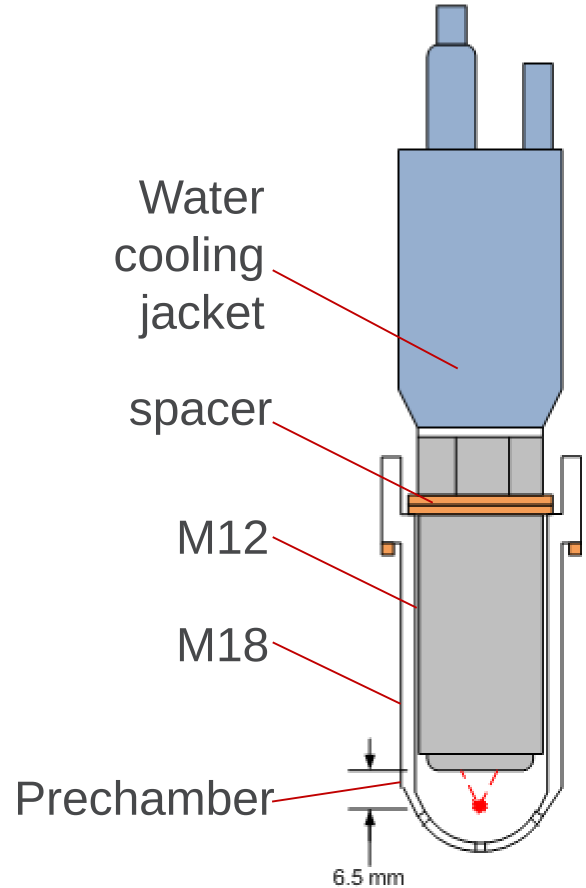
FOUR DIFFERENT GEOMETRIES WERE TESTED

SI



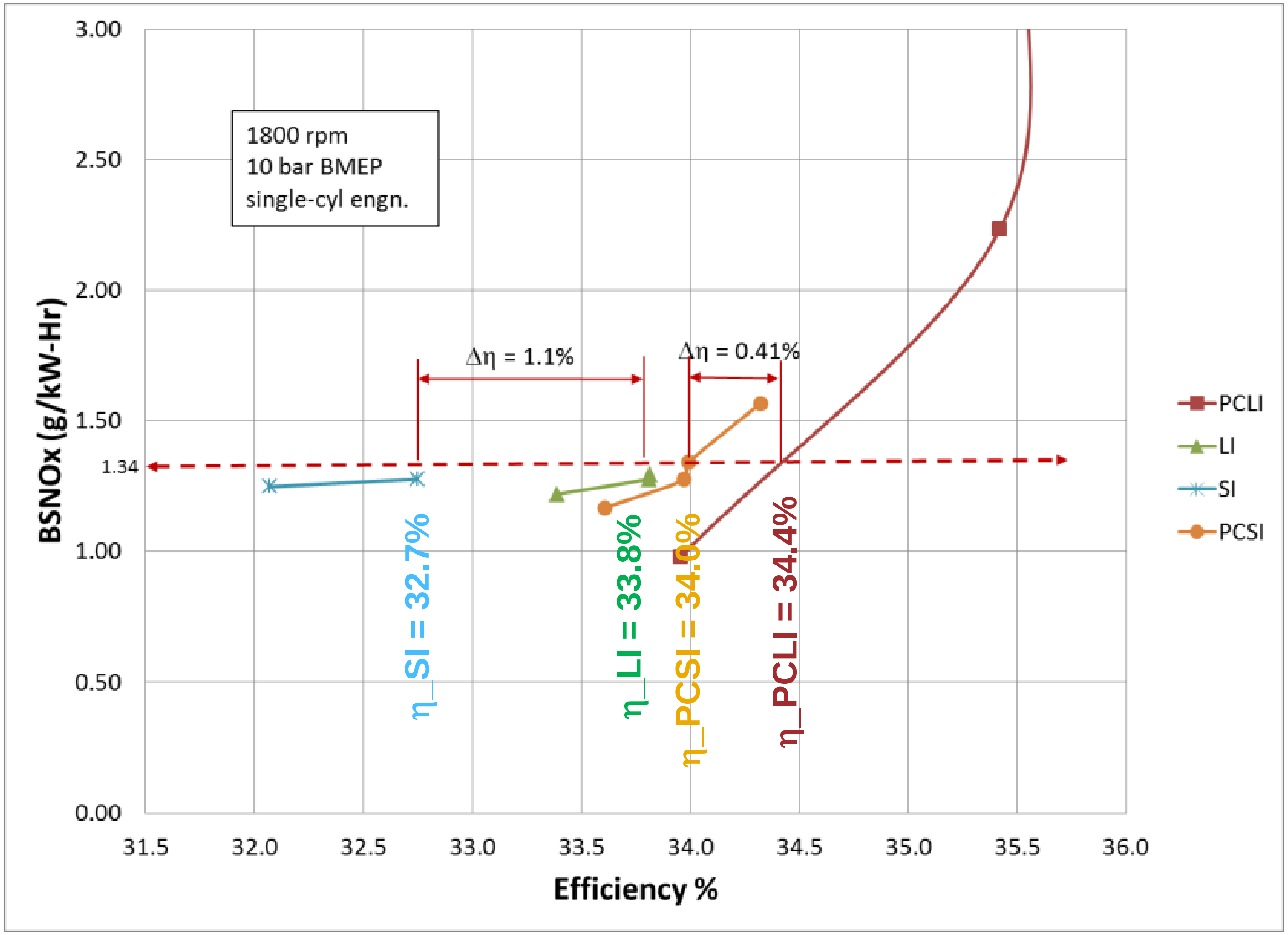
LI

PCSI



PCLI

RESULTS



* (Flame jet ignition + Laser ignition) is extremely effective.

VISUALIZATION OF NATURAL GAS COMBUSTION IN ENGINES

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VISUALIZATION OF NATURAL GAS COMBUSTION IN ENGINES

Opportunity: Engine efficiency, emissions, and power density demands are limited by igniters. In-cylinder combustion visualization enables evaluation and development of advanced ignition systems for engines

Objective: To evaluate advanced ignition systems and study the effect of flame kernel influence on engine performance using imaging and numerical analysis

Imaging enables detailed study of:

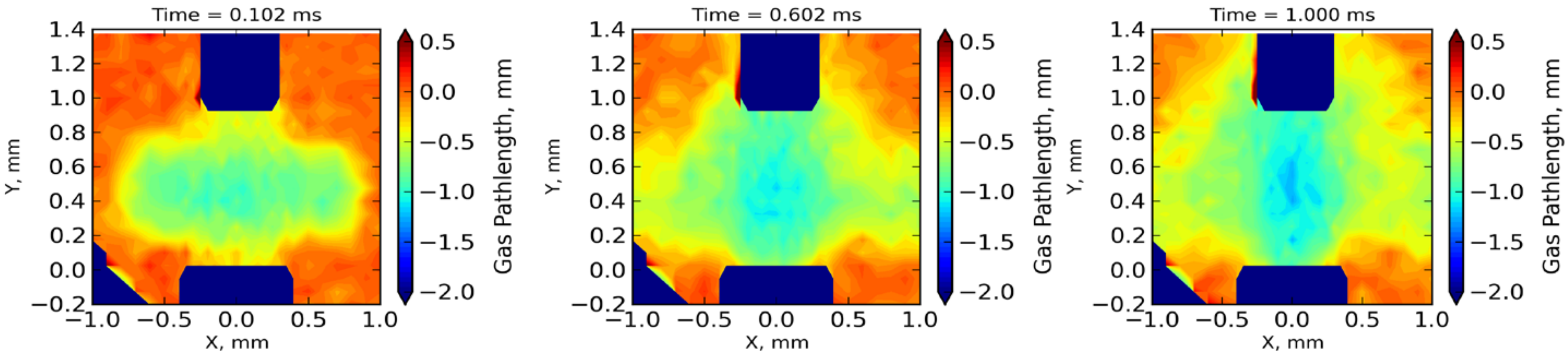
- Combustion phenomenon of different igniters
- Spark properties: flux intensity, variability, repeatability, and performance
- Flame kernel characterization
- Laser spark: Influence of multiple consecutive/concurrent sparks and spark distance (from fire deck) on combustion

X-ray Imaging of Spark at Advanced Photon Source (APS):

- X-ray measurements of spark from an automotive spark plug at 3 bar in air, coil charge time: 2.5 ms; Coil energy: 75 mJ
- X-rays provide a direct measurement of gas density, and do not suffer from interference from the light produced by the spark
- We are using x-ray radiography to quantitatively measure the gas density field around a spark

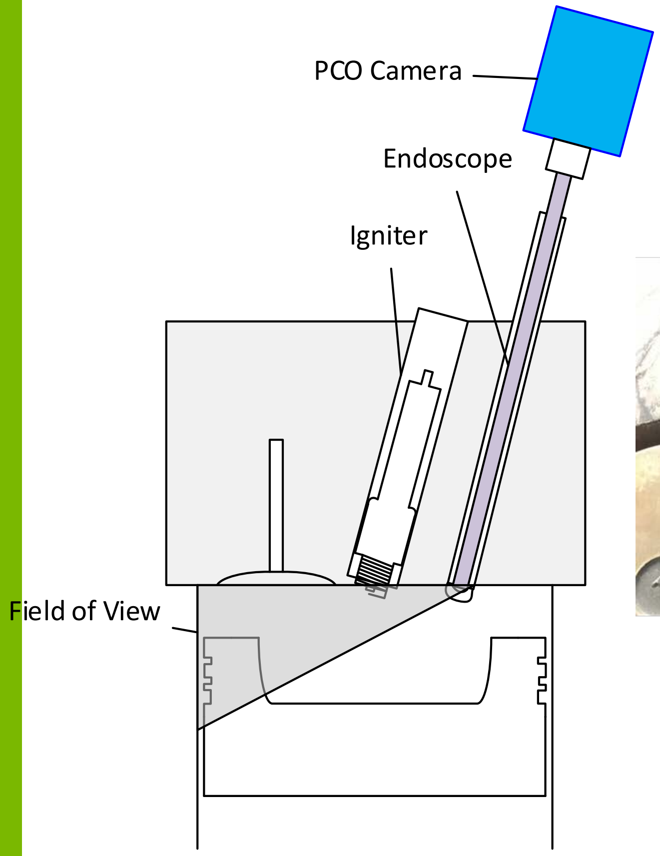
Numerical Evaluation of Ignition Systems

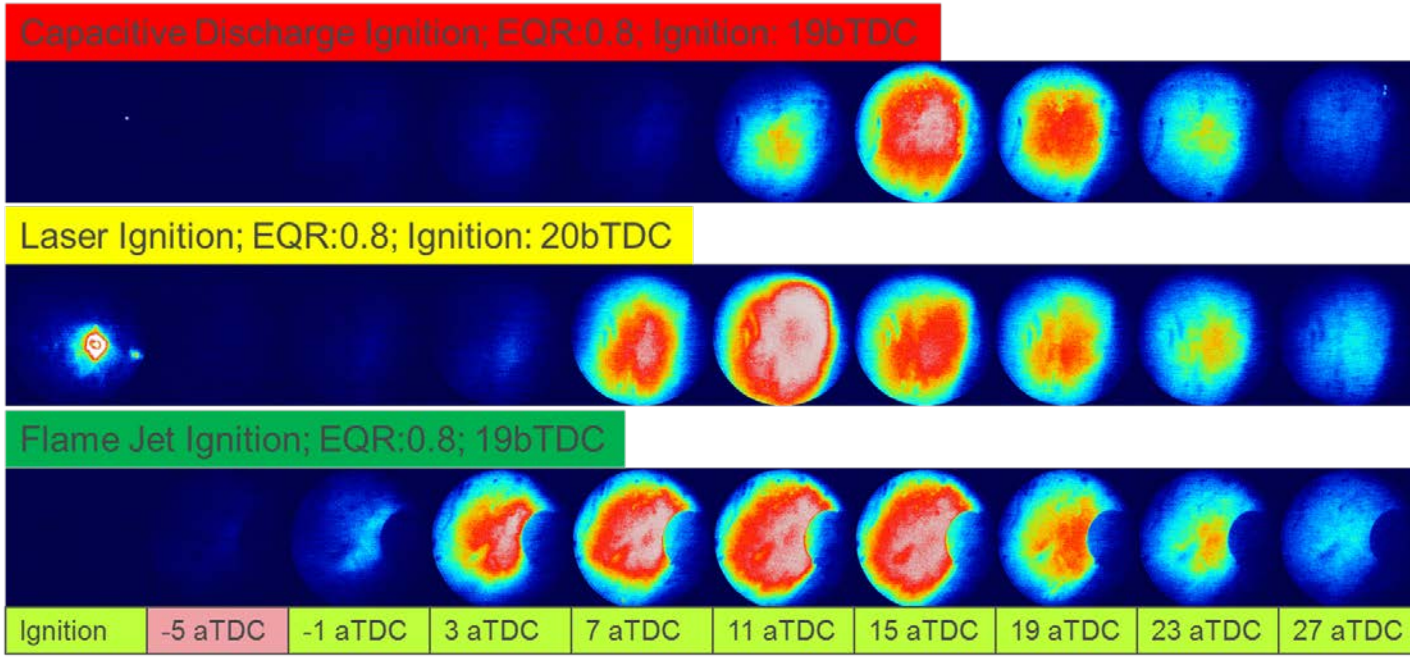
- Energy deposition model (EDM) adopted for conventional ignition
- EDM is being modified for laser generated plasma
- Detailed simulation of temperature and density profiles of laser induced plasma relevant to combustion engines



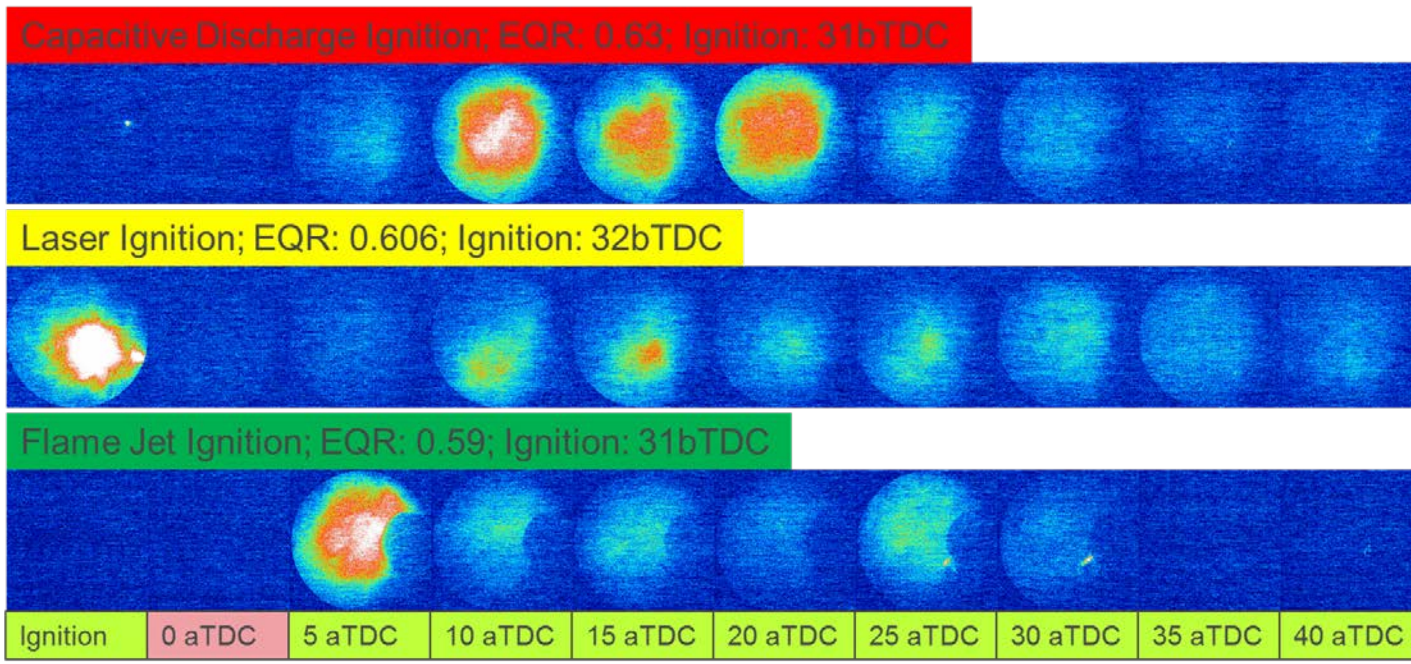
Imaging of Advanced Ignition Systems:

- Capacitive Discharge Ignition (CDI): Altronic CD200 (35-40 mJ)
- Laser Ignition: BigSky Nd:YAG 532nm (20-25 mJ, PulseWidth: ~7ns)
- Flame Jet Ignition: 18mm Adapter with 5 holes (Hole Ø: 2.2mm)





Better ignition w.r.t CDI



Leaner mode w.r.t CDI

Results and Accomplishments:

Ignition and combustion images of CDI, Laser, and FJI highlight the influence of igniter type on combustion.

- CDI: Lean limit (0.63),
- LI: Extends lean limit (0.61), lower NOx
- FJI: NOx 40%<CDI, 14%<LI with comparable efficiency

Future Work:

- High speed imaging of ignition event
- Flame kernel characterization
- Simultaneous imaging of multiple field of views
- Imaging of alternate ignition systems
- X-ray measurements of laser spark
- Extension of numerical analysis to different igniters

ADDITIVE MANUFACTURING FOR COMBINED HEAT AND POWER

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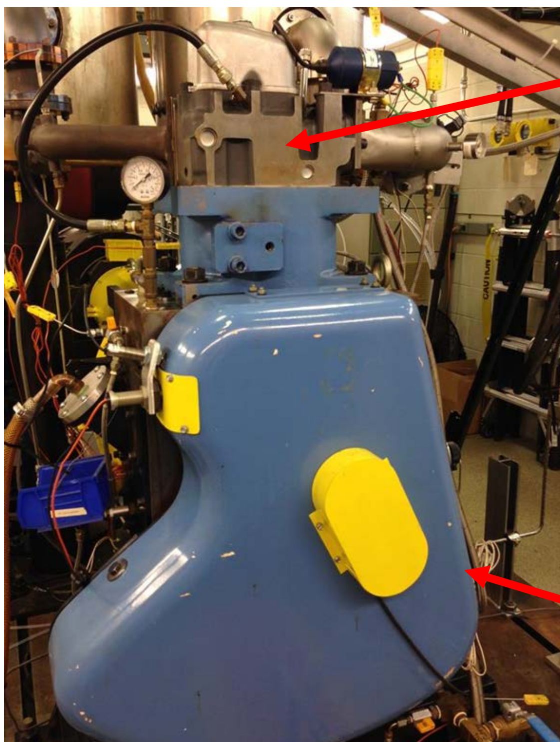
Opportunity: Additive Manufacturing (AM) enables:

- Rapid prototyping of complex contoured features in engine components
- Optimized materials to improve heat transfer characteristics
- Adoption of advanced igniters for different engine platforms
- Higher engine efficiency in distributed generation systems

Objective: Demonstration of AM as a viable rapid prototyping method to manufacture custom engine components that improves engine efficiency.



Additive Manufactured Engine Cylinder Head (ORNL)

Argonne's Single Cylinder Research Engine

Methodology:

- Collaboration between Argonne (ANL) and Oak Ridge National Laboratories (ORNL)
- Argonne's Single Cylinder Research Engine was selected due to its open architecture, flex fuel capability, and expertise on gas engine research for combined heat and power.
- ORNL generated a 3-D model of the engine's cylinder head
- ORNL's manufacturing demonstration facility (MDF) evaluated AM to fabricate high strength bimetallic samples (Tungsten-steel, tungsten-molybdenum, tungsten-bronze)
- ORNL is evaluating a binder-jet process to print engine components designed to enable high efficiency, lean combustion modes.
- Argonne will install the AM cylinder head on the research engine and evaluate the engine performance
- Advanced combustion concepts using prototype igniters will be explored to develop engine technologies