Diode Pumped Passively Q-switched Laser Spark Plug Development and Progress

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Overview

• The Problem
• Why Laser Ignition?
  – Combustion, Emissions, Durability
• Laser Development
  – Basics
  – Objectives
• Approach
  – Theory and Modeling
  – Experimentation
• Results
• Conclusions
• Future Direction
  – End pumped laser spark plug
The Problem

• Large Bore Stationary Natural Gas Engines
  – Gas Pipeline Pumping
  – Power Generation

• Market Driven Efficiency Barriers
  – Lean Burn Ignitability
  – Ignition System Durability
  – Engine Maintenance Downtime
  – NOx Emissions
Why Laser Ignition?

**Combustion**
- Leaner/Cooler Combustion
- Increased Thermal Efficiency at Higher Operating Pressures
- Improved Combustion Stability
- Favorable Laser Spark Pressure Dependence

**Emissions**
- Lower NOx Production

**Durability**
- No heat loss to electrodes, more energy to fuel/air mix
- Laser window/lens is self cleaning
Why Laser Ignition?

Electrical Spark Breakdown Threshold vs. Pressure

Laser Spark Breakdown Threshold vs. Pressure

- Buscher Argon
- Buscher xenon
- Ready Ar
- Ready Xe
- Ready N2
- Phouc Air
- Tomlinson Air
- Phouc CH4
Previous NETL Laser Ignition Engine Research

- Reduced NOx emissions
- Improvement of Combustion Stability
- Leaner Operation than Conventional Spark Plug
- Misfire Limit extended from A/F ratio of 0.535 to 0.513
- Ignition delay 7% shorter with laser spark

Prior Art Problems

- Flashlamp pumped lasers are highly inefficient and require high voltage
- Active Q-switching is expensive, requires high voltage, and precise timing
- Multiple wavelength and multiple pulse breakdown techniques for laser spark are complex
- Complicated designs require more parts and more control hardware
Approach

• **Independent Variables**
  – Output Coupler Reflectivity
  – Q-switch Initial Transmission
  – Active Ion (Nd) Concentration
  – Pump Power

• **Dependent Variables**
  – Output Pulse Energy
  – Output Pulse Width
  – Pulse Delay Time
  – \( M^2 \) – Beam Quality

• **Derived Dependent Variables**
  – Peak Power
  – Focal Intensity
  – Pulse Efficiency
Side Pumped Laser

Laser Spark Plug Description
Diode Pumped (Side Pumped) - High Efficiency, Low Voltage

- Passively Q-switched (Cr:YAG) – No External Control, Low Jitter
- Small Size (126mmX50.8mm) – Prototype, Can Be Smaller
- Produces Single High Peak Power Pulse with Timed Pulse Pump
- Simple Design and Operation
- Passively or Actively Cooled Diodes and YAG Rod (TEC’s and/or Liquid) –
Approach

- Numerical Model showing maximum attainable output pulse energy for a range of optical combinations
- Heavy line indicates optimum output coupling
- Test Matrix (in red) represents realistic expectations based on preliminary experimental testing
- Test Matrix is pump power limited
Output Pulse Energy

Nd 0.35% Pump Power 1007 Watts

Output Pulse Energy (mJ)

Output Coupler Reflectivity

Q-Switch Initial Transmission

Output Pulse Energy

Output Coupler Reflectivity

Q-Switch Initial Transmission

10.00
11.00
12.00
13.00
14.00
15.00
16.00
17.00
18.00
19.00
20.00
21.00
22.00
23.00
24.00
25.00
26.00
27.00
28.00
29.00
30.00
Output Pulse Width

Nd 0.35% Pump Power 1007 Watts

Output Pulse Width (ns)

Q-Switch Initial Transmission

Output Coupler Reflectivity
Beam Quality

Nd 0.35% Pump Power 1007 Watts

Times Diffraction Limited - $M^2$

Q-Switch Initial Transmission

Output Coupler Reflectivity
Focal Intensity

Nd 0.35% Pump Power 1007 Watts

Focal Intensity (GW/cm²)

Output Coupler Reflectivity

Q-Switch Initial Transmission

1.00.E+11
1.25.E+11
1.50.E+11
1.75.E+11
2.00.E+11
2.25.E+11
2.50.E+11
2.75.E+11
3.00.E+11
3.25.E+11
3.50.E+11
3.75.E+11
4.00.E+11
4.25.E+11
4.50.E+11

30
50
40
36
32
Summary of Experimental Testing

- Increasing pump power beyond threshold has little effect on laser output
- Increasing pump power results in a faster output pulse
- Decreasing the output coupler reflectivity results in higher output pulse energy
- Decreasing the Q-switch initial transmission results in higher output pulse energy
- Reduction of Nd concentration results in higher output pulse energy and improved beam quality
Status of Development

- Side pumped laser spark plug reduced to practice in the lab
- Passive Q-switch
- Produces spark with ~2.0 MW pulses at a rate of 6 Hz and greater
- Needs to be ruggedized for reliable on engine operation
- Diode pump bars are greatest cost component

Future Direction

- End pumped laser has higher slope efficiency
- Better for fiber coupling
- Pump laser distributes better through fiber than high energy pulses
- Designed and assembled, ready for testing
Future Direction

- End pumped laser spark plug
NETL Model Spark Plug System

- **Spark Plug**
  - Nd:YAG laser, passively Q-switched
  - Pump energy delivered through fiber optic

- **Optical Distributor**
  - Distributes pump energy to spark plugs
  - Low peak power in fiber optics, <1000 watts

- **Pump Laser**
  - Diode lasers at 808 nm
  - Fiber optic coupled
  - Pump pulse controls timing
End Pumped Laser Prototype

Output Coupler  Nd:YAG Rod  Pump Transmitting End Mirror

Pump Coupling Lens  Pump Relay Optical Fiber

25 mm
Distributor Lab Prototype

Rotating Wedge Prism
Collimating Lens
Power Input Fiber

Drive Motor
Optical Distributor for distribution of pump light or laser pulse

Preferred embodiment: rotating prism is not susceptible to misalignment during rotation; small radial distribution of fibers gives adequate dwell time for laser pulse and allows for timing adjustment.
Issues

• Pump delivery fiber is currently spec’ed at 1 mm
• Pump diameter at the end pumped laser will be 1 mm or greater
• To maximize pump and laser beam overlap, the end mirrors will need to be flat-flat or very long radius of curvature (>10 m)
• Maintaining near 1 mm pump beam diameter also requires short Rayleigh range, and therefore a short laser rod
Conclusions

• Side pumped laser focal intensities were achieved that produced robust spark

• Best performance when...
  – Output coupler reflectivity was approx. 30%
  – Q-switch initial transmission was approx. 32%
  – Nd concentration was 0.35%
  – Pump power exceeded 1kW

• Ignition system is feasible with proper mechanical and thermal refinement

• End pumped laser predicted to offer improved performance