Burst Mode Lasers

Presented by:

OSA Laser Systems Technical Group
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BURST MODE LASERS WEBINAR
11 December 2019 • 13:30 EST
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Technical Group at a Glance

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  • This group encompasses novel laser system development for a broad range of scientific, industrial, medical, remote sensing and other directed-energy applications.

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Today’s Webinar

Burst Mode Lasers Webinar

Dr. Josef Felver
Spectral Energies LLC
josef.felver@spectralenergies.com

Speaker’s Short Bio:
Dr. Josef Felver’s specialization is the development and application of burst-mode laser systems with a focus on system integration and software control. He holds a doctoral degree in Physics from Washington State University.
Burst-Mode Lasers

Josef Felver
Outline

• Laser architecture and capabilities
• Diagnostic techniques
• Outlook
Motivation

• Reacting flow models validation
• Studies of flame instabilities
• Diagnostics of new engines
Pulse-burst laser approach

(a) CW laser is sliced into pulse train

(b) Nd:YAG gain curve

(c) Result is high power "burst" of 1~99 pulses

(Based on Lempert and Miles, et. al., AIAA-96-0500, 1996)
### Brief History of Burst-Mode Lasers

**Burst-Mode Lasers (“Pulse-burst”)**

- **Princeton – R. Miles**
  - 500 kHz, 100 µs (PDV)
- **NASA Glenn – M. Wernet**
  - 1 MHz, <100 µs (PIV)
- **Ohio State – W. Lempert**
  - 10-1000 kHz, 1 ms
  - NO PLIF visualization
- **Auburn – B. Thurow**
  - 3D scanning flow visualization
- **Ohio State – J. Sutton**
  - Raman, Rayleigh (10 kHz, 10 ms)
- **AFRL/Iowa State – Roy, Meyer, Gord**
  - OH, NO, CH₂O PLIF, Mixture fraction, PIV
  - 5-100 kHz, up to 30 ms

![Image of Burst-Mode Lasers](image)

**References**

Necessity of High-Fidelity Measurements

Comparing 4 different state-of-the-art reacting LES codes on the Volvo bluff body test case:
Premixed Propane-Air, Re = 40,000, 288 K, Equivalence Ratio = 0.65

CharLES

LESLIE3D

OpenFOAM

Fluent

Instantaneous temperature Contours

All using the same grid, time-step, boundary conditions, and physical models: All give completely different answers!

- DNS not applicable to large scales yet: LES numerics and grid dependencies still exist even for simple problems.
- LES uses sub-grid models for turbulence-chemistry interactions – How do we know if models and global, system-level interactions are accurately understood under relevant high thermal power conditions?

Why laser diagnostics?

Particle image velocimetry (PIV)

1. Subdivide image into interrogation spots
2. Cross-correlation
3. Peak search

Laser 1: Image A
Laser 2: Image B

http://cav.safl.umn.edu/Facilities/piv.htm
Why laser diagnostics?

Laser spectroscopy

Spectrum can be related to the thermodynamic state of the gas

- Line frequency
- Line intensity
- Line width

speed
pressure
concentration
temperature

Species:
- N₂
- O₂
- H₂
- CO₂
- H₂O

Radicals:
- OH
- C₂
- CH
- CH₂O

Pollutants:
- NO
- CO
Pulse-burst laser layout
Burst-mode: high-energy output

![Graph showing pulse energy vs. repetition rate for different burst modes and sources.]

- Burst-mode: high-energy output
  - Pulse energy (mJ)
  - Repetition rate (kHz)
  - Burst duration
  - 10 Hz Nd:YAG
  - DPSS
Diode pumping: 100-ms Burst Duration


Diode array split for enhanced overlap


~4× higher than DPSS at 10 kHz

1,000 pulses

~7× higher

10,000 pulses
Pulse-burst laser flexibility

Pulse sequence shaping at high-repetition-rates via modulation of master oscillator
Flexible oscillator: Pulse Shaping

Input

(A)

Output

(B)

Intensity (A.U.)

Time (ns)

- 16 ns
- 42 ns
- 90 ns
- 189 ns
- 285 ns

- 12 ns
- 27 ns
- 53 ns
- 111 ns
- 169 ns
Flexible oscillator: Pulse Shaping
Flexible oscillator: Dual-pulse operation

![Graph showing input and output power over time](image)

- **Input power (a.u.)**
  - 0.000
  - 0.005
  - 0.010
  - 0.015
- **Output power (a.u.)**
  - 0.0
  - 0.2
  - 0.4
  - 0.6
  - 0.8
  - 1.0

- **Time (µsec)**
  - -1
  - 0
  - 1
  - 2

![Graph showing ratio of power](image)

- **Ratio \( E/E_{intensity,1} \)**
  - 0.0
  - 0.2
  - 0.4
  - 0.6
  - 0.8
  - 1.0

- **Repetition rate (kHz)**
  - 0
  - 20
  - 40
  - 60
  - 80
  - 100

- **Input power (a.u.) vs. Output power (a.u.)**
- **Camera frames**
- **Pulse Pair**
- **Measured (\( dt=1 \) µsec)**
- **Model**
10,000-frame, 100-kHz Stereo TR-PIV

10-kHz PIV is insufficient to resolve high-speed structures

Stereo PIV along centerline of a Mach 0.3 free jet with Re = 30,000.
Up to 4 mJ per pulse at 100 kHz with 1 µs inter-pulse spacing.

\( v_y = 102 \text{ m/s} \)

\( f = 100 \text{ kHz} \)

Playback at 50 µs/s

Miller et. al. 2015
25 and 50 kHz TR-PIV in Trisonic Wind Tunnel
Mach 3.7 jet issuing into a Mach 0.8 crossflow

S. Beresh et. al. 2015
Transient Wake Vorticity Behind Cylinder

175 m/s
Re = 1.8 × 10^5

Flow

50 kHz pulse pairs
20 mJ/pulse @532nm

Final interrogation window: 24 × 24 pix (1.8 × 1.8 mm^2)

Vortex shedding starts symmetric, then becomes a von Kármán street.

Wagner et. al., 2016 doi:10.2514/6.2016-0791
Development of a compact 14 J Nd:YAG burst-mode laser for PIV

- Sufficient PIV capabilities
- Easy transportation and more lab space
- Cost effective
Higher Harmonics

- 532 nm
- 1064 nm
- 355 nm
- 266 nm

SHG  THG  FHG

\( \lambda/2 \)

1064 nm  532 nm  355 nm  266 nm
50 and 100 kHz formaldehyde PLIF Mach 2 scramjet flameholder

Burst-mode laser applied to characterize spark and pulse-detonator ignition and flameholding in RQH Research Cell 19 with Drs. Cam Carter and Scott Peltier

Miller et. al. 2015
Formaldehyde PLIF and Chemiluminescence

50 kHz, 75 SLPM $C_2H_4$

- Spark
- Detonator
- Failed Detonator
50 and 100 kHz formaldehyde PLIF
Mach 2 scramjet flameholder

Formaldehyde PLIF and Chemiluminescence

50 kHz, 75 SLPM C₂H₄

Side camera
PLIF

Top camera
Chemiluminescence

Spark
Detonator
Failed Detonator
High-Speed 3D Combustion Species Measurements

20-kHz Tomo Acetone LIF

20 kHz Tomo CH$_2$O LIF

10 kHz Tomo LII

Halls et al. Optics letters 42 (14), 2830-2833 (2017)

Meyer et al., Optics express 24 (26), 29547-29555 (2016)

Multi-Leg Burst Mode Laser
Multi-Leg Burst Mode Laser

Simultaneous Measurements of Velocity and Scalars in Reacting Flows at 10 kHz

- OPO enabling wavelength tuning capability for OH LIF excitation
- Double pulse capability for PIV

The unique laser system is capable of simultaneously measuring velocity and concentrations of OH and CH$_2$O at a rate of 10 kHz

- Ability to identify the reaction zone, preheat zone, and flow velocity vector field with a single laser system

Roy et al., Optics letters 43 (11), 2704-2707 (2018)
Picosecond Burst-mode Laser

Pulse width flexibility using an 80-MHz picosecond oscillator incorporated into burst-mode laser architecture

Picosecond Burst-mode Laser

Self Focusing Damage to Nd:YAG Rod
Picosecond Burst-mode Laser

- Picosecond Laser Electronic-Excitation Tagging
Coherent anti-Stokes Raman scattering

The pump, $\omega_p$, Stokes, $\omega_S$, and probe, $\omega_{pr}$, electric fields induce third order polarization:

$$P_{CARS}^{(3)} (\omega_{as}) = \omega_p + \omega_S + \omega_{pr}$$

where

$$\chi_{eff}^{(3)} = \chi_{NR}^{(3)}$$

This polarization gives rise to the following transitions:

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Transition, cm$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{H}_2\text{S(3)}$</td>
<td>1050</td>
</tr>
<tr>
<td>$\text{CO}_2$</td>
<td>1275</td>
</tr>
<tr>
<td>$\text{C}_2\text{H}_4$</td>
<td>1340</td>
</tr>
<tr>
<td>$\text{CO}_2$</td>
<td>1388</td>
</tr>
<tr>
<td>$\text{H}_2\text{S(5)}$</td>
<td>1400</td>
</tr>
<tr>
<td>$\text{CH}_4$</td>
<td>1535</td>
</tr>
<tr>
<td>$\text{O}_2$</td>
<td>1555</td>
</tr>
<tr>
<td>$\text{C}_2\text{H}_4$</td>
<td>1625</td>
</tr>
<tr>
<td>$\text{H}_2\text{S(6)}$</td>
<td>1650</td>
</tr>
<tr>
<td>$\text{CO}$</td>
<td>2143</td>
</tr>
<tr>
<td>$\text{N}_2$</td>
<td>2331</td>
</tr>
<tr>
<td>Hydrocarbons</td>
<td>2900 - 3200</td>
</tr>
</tbody>
</table>

100 kHz burst-mode CARS layout

Burst-mode OPG/OPA performance

(a) Pump Energy (mJ/pulse) vs. Time (ms)

(b) OPG/OPA Energy (mJ/pulse) vs. Time (ms)

(c) Intensity (Norm.) vs. Wavelength (nm)

(d) OPG/OPA Energy (mJ/pulse) vs. Pump (mJ/pulse)

\[ E_{\text{OPG}} = 1.2e^{-8} \times E_{\text{pump}}^{4.87} \]
100-kHz CARS H$_2$ thermometry

Jet diffusion flame
Re $\sim$ 10,000

Captured dynamical change in temperature in highly turbulent flame at 100 kHz rate

1-kHz Single-Shot 2D CARS

100-ps Burst-Mode
5 mJ @ 1 kHz, 532 nm

100-fs Regen
2 mJ @ 1 kHz, 800 nm

From fs oscillator

1 kHz from regen

1 kHz from regen

1 kHz
1064 nm

80 MHz

PD2

Bias control

PD1

ps PG

RF Amp

cw DL

EOM

1x2

Yb FA

AOM

PG

PA

Miller (2016)
**1 kHz Temperature Imaging in a High-Speed Heated Jet**

**Steady-State Temperature Analysis**

<table>
<thead>
<tr>
<th>T = 295 K</th>
<th>IRO Gain</th>
<th>$T_{\text{avg}}$ [K], (%)</th>
<th>$T_{\text{RMS},x}$ [K], (%)</th>
<th>$T_{\text{RMS},t}$ [K], (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O$_2$</td>
<td>35%</td>
<td>287.2 (2.6%)</td>
<td>27.1 (9.4%)</td>
<td>7.4 (2.6%)</td>
</tr>
</tbody>
</table>

Spatial Res. @ 20% MTF = 79 µm (~ 3 pix)

Dispersion = 0.1 cm$^{-1}$/pix, Spectral Instrument Function = 0.46 cm$^{-1}$ (~4.5 pix)

Miller (2016)
Advantages of burst-mode lasers

- Order of magnitude higher pulse energies compared to continuously pulsed lasers
- Flexible repetition rate (1 – 10 MHz)
- Flexible pulse duration (100 ps – 10 μs)
- Inherent PIV capabilities
- External triggering, cold start
## SYSTEM SPECS

<table>
<thead>
<tr>
<th>Quasimodo Model</th>
<th>1200</th>
<th>150</th>
<th>1500</th>
<th>100 ps option</th>
</tr>
</thead>
<tbody>
<tr>
<td>Individual pulse width</td>
<td>10-15 ns</td>
<td>10-15 ns</td>
<td>10-15 ns</td>
<td>100 ps</td>
</tr>
<tr>
<td>Pulse frequency within a Burst</td>
<td>2-100 kHz</td>
<td>2-100 kHz</td>
<td>2-100 kHz</td>
<td>2-100 kHz</td>
</tr>
<tr>
<td>Number of pulses in Burst</td>
<td>100 @ 10 kHz</td>
<td>100 @ 10 kHz</td>
<td>100 @ 10 kHz</td>
<td>100 @ 10 kHz</td>
</tr>
<tr>
<td>Duration of Burst</td>
<td>1-10 ms</td>
<td>1-10 ms</td>
<td>1-10 ms</td>
<td>1-10 ms</td>
</tr>
<tr>
<td>Typical pulse energies (mJ) @ 10 kHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1064 nm</td>
<td>1000 (Limited)</td>
<td>100</td>
<td>1000 (Limited)</td>
<td>200</td>
</tr>
<tr>
<td>532 nm</td>
<td>500</td>
<td>50</td>
<td>500</td>
<td>100</td>
</tr>
<tr>
<td>355 nm</td>
<td>250</td>
<td>20</td>
<td>250</td>
<td>NA</td>
</tr>
<tr>
<td>266 nm</td>
<td>70</td>
<td>3</td>
<td>70</td>
<td>NA</td>
</tr>
<tr>
<td>Typical pulse energies (mJ) @ 100 kHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1064 nm</td>
<td>100</td>
<td>15</td>
<td>150</td>
<td>120</td>
</tr>
<tr>
<td>532 nm</td>
<td>50</td>
<td>5</td>
<td>70</td>
<td>60</td>
</tr>
<tr>
<td>355 nm</td>
<td>25</td>
<td>NA</td>
<td>30</td>
<td>NA</td>
</tr>
<tr>
<td>266 nm</td>
<td>3</td>
<td>NA</td>
<td>5</td>
<td>NA</td>
</tr>
<tr>
<td>Time between pulse sequences</td>
<td>12 seconds</td>
<td>12 seconds</td>
<td>12 seconds</td>
<td>12 seconds</td>
</tr>
<tr>
<td>Spectral Bandwidth</td>
<td>&lt; 1 GHz</td>
<td>&lt; 1 GHz</td>
<td>&lt; 1 GHz</td>
<td>&lt; 10 GHz</td>
</tr>
<tr>
<td>Beam diameter, 1/e²</td>
<td>4 - 7 mm</td>
<td>2.5 - 5 mm</td>
<td>4 - 7 mm</td>
<td>4 - 7 mm</td>
</tr>
<tr>
<td>Beam quality, M⁰</td>
<td>&lt; 5</td>
<td>&lt; 5</td>
<td>&lt; 5</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>Pulse sequence flatness with optional tailored profile control</td>
<td>&gt;0.90</td>
<td>&gt;0.90</td>
<td>&gt;0.90</td>
<td>&gt;0.90</td>
</tr>
</tbody>
</table>
Outlook

- MHz-rate 2D and 3D imaging
- Going femtoseconds (1 MHz 2D CARS)
- 100 kHz – 1 MHz tunable sources
Future work: Spatio-Temporally Evolving Complex Flows

• Supersonic combustion wave, Mach > 7
  • 4D cellular wave front structure, requiring MHz time resolution to track!
• Multiphase flows in explosives, particles of varying sizes, gas/solid phase velocities
  • Most subsonic, supersonic, and high-speed systems

Unpublished work at Purdue
Summary

✔ Transportable system
✔ Generation of stable 100-ms bursts (RMS ~2%)
✔ Extension of TDR (5,000)
✔ Pulse amplitude shaping for burst flatness enhancement
✔ Extension to picosecond pulse widths (<100 ps)
✔ Highly efficient SHG (~70%) using ps burst-mode laser
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