Burst Mode Lasers

Presented by:

OSA Laser Systems Technical Group

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Technical Group at a Glance

- Focus
  - This group encompasses novel laser system development for a broad range of scientific, industrial, medical, remote sensing and other directed-energy applications.
- Mission
  - To benefit *YOU*
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Today's Webinar

Burst Mode Lasers Webinar

Dr. Josef Felver

Spectral Energies LLC

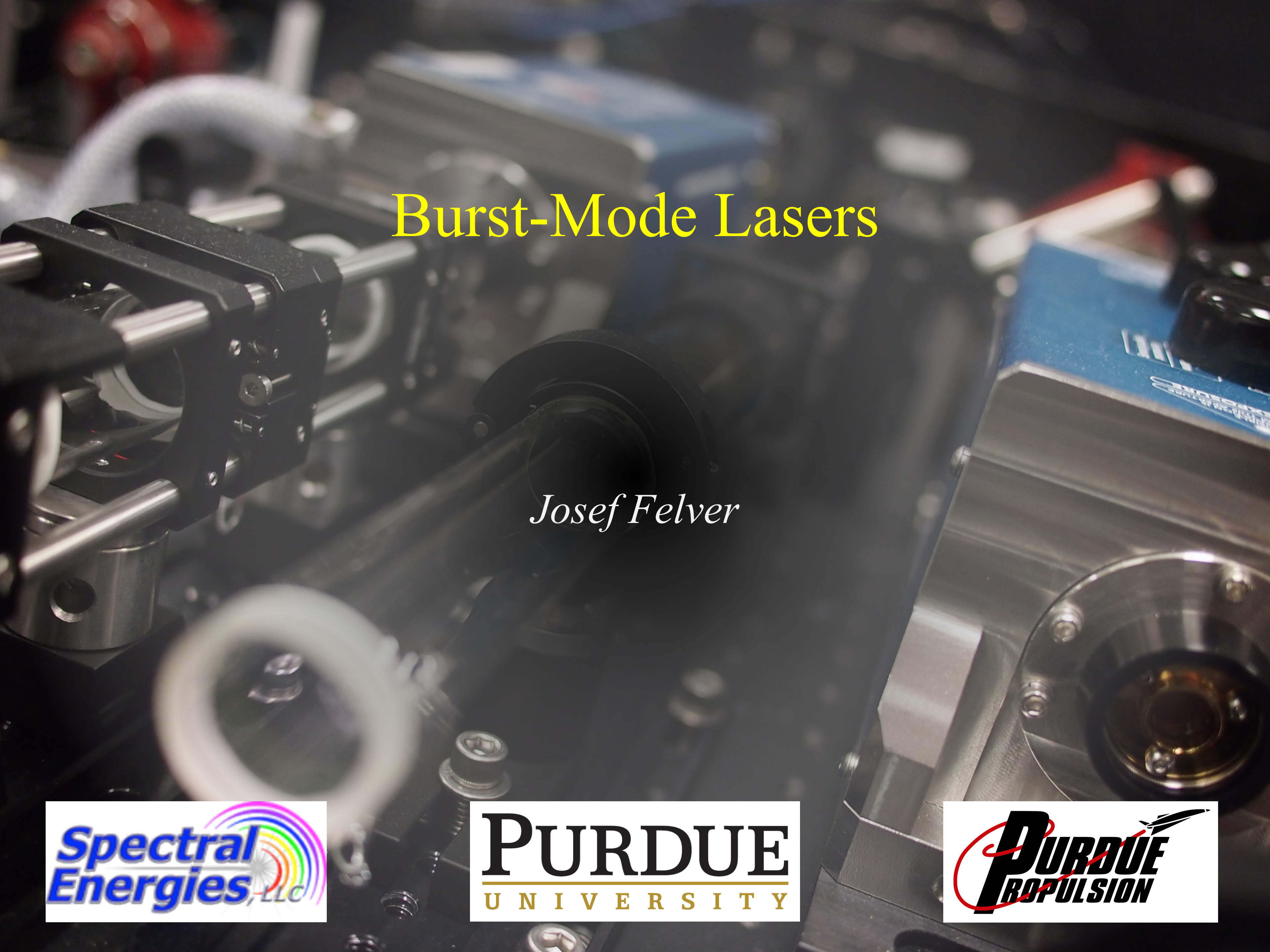
josef.felver@spectralenergies.com

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

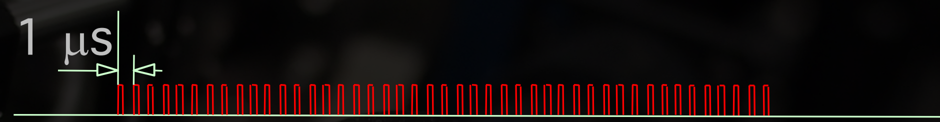
- Laser architecture and capabilities
- Diagnostic techniques
- Outlook

Motivation

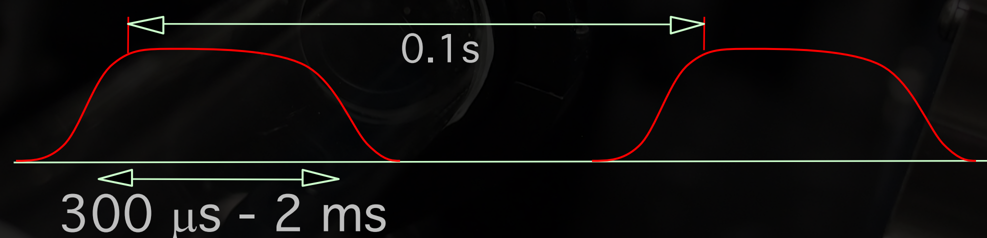
- Reacting flow models validation
- Studies of flame instabilities
- Diagnostics of new engines

Pulse-burst laser approach

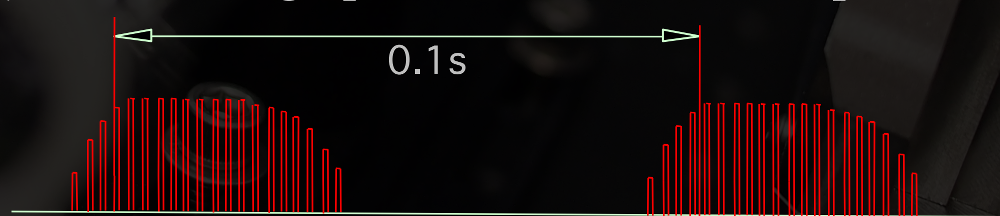
(a) CW laser is sliced into pulse train



(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

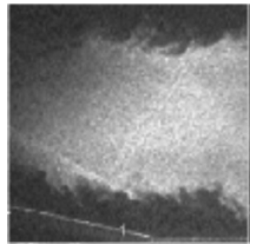
Burst-Mode Lasers (“Pulse-burst”)

•Princeton – R. Miles

- **500 kHz, 100 µs** (PDV)

•NASA Glenn – M. Wernet

- **1 MHz, <100 µs** (PIV)

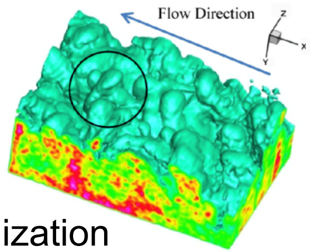


•Ohio State – W. Lempert

- **10-1000 kHz, 1 ms**
- NO PLIF visualization

•Auburn – B. Thurow

- 3D scanning flow visualization

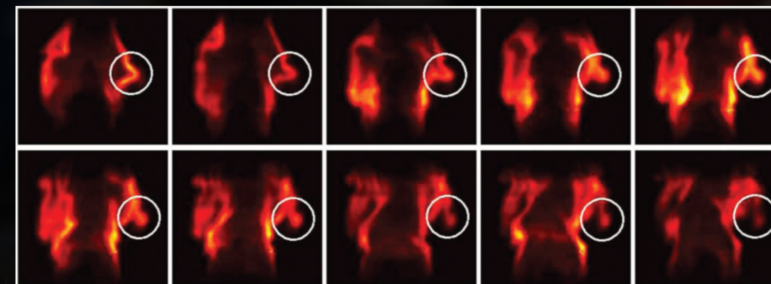


•Ohio State – J. Sutton

- Raman, Rayleigh **(10 kHz, 10 ms)**

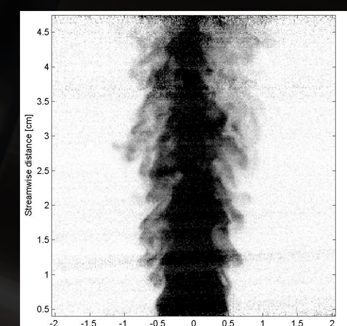
•AFRL/Iowa State – Roy, Meyer, Gord

- OH, NO, CH_2O PLIF, Mixture fraction, PIV
- **5-100 kHz, up to 30 ms**

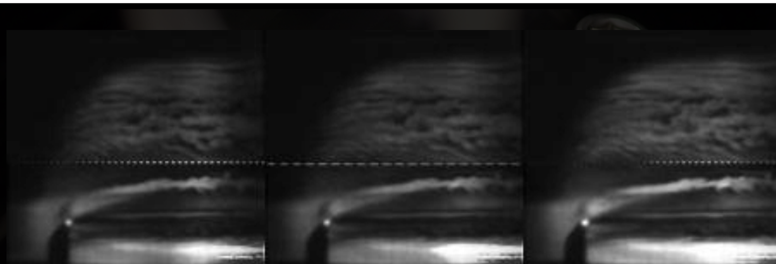


Miller, Slipchenko *et al.*, Opt. Lett. (2009)

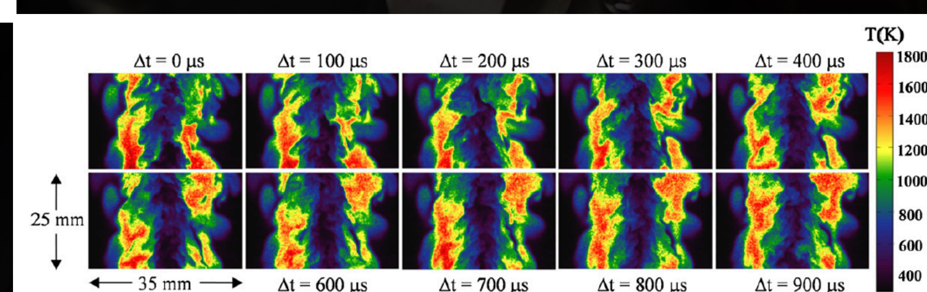
Slipchenko, Opt. Lett. (2012)



Miller, Appl. Phys. B (2013)



Jiang, Appl. Opt. (2011)

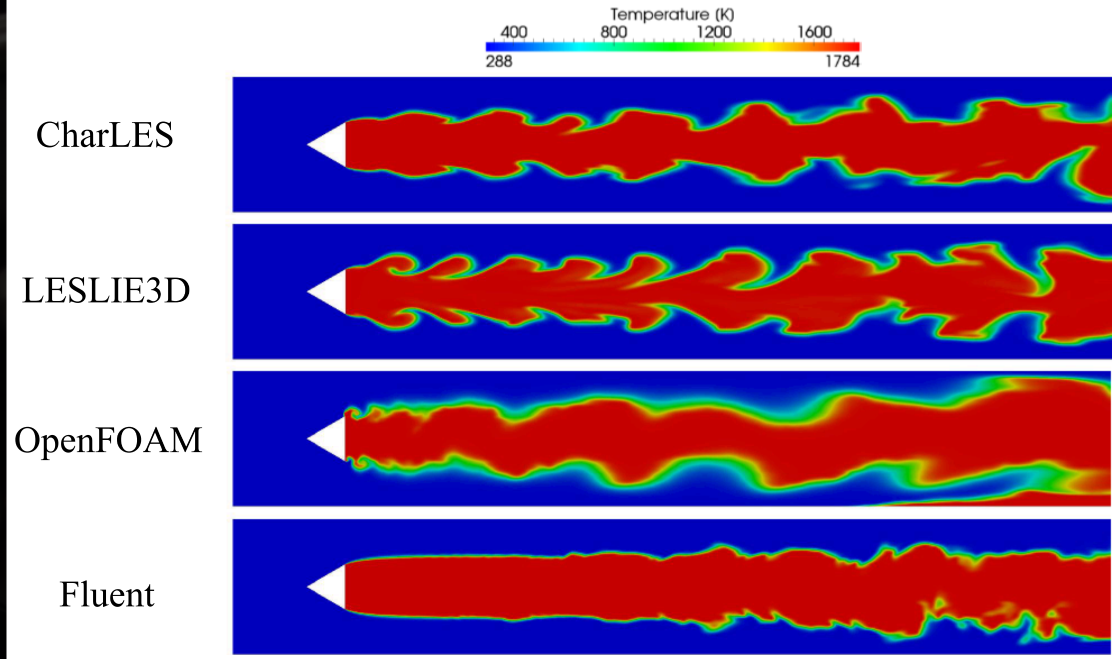


Patton, Appl. Phys. B. (2012)

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



Instantaneous temperature Contours

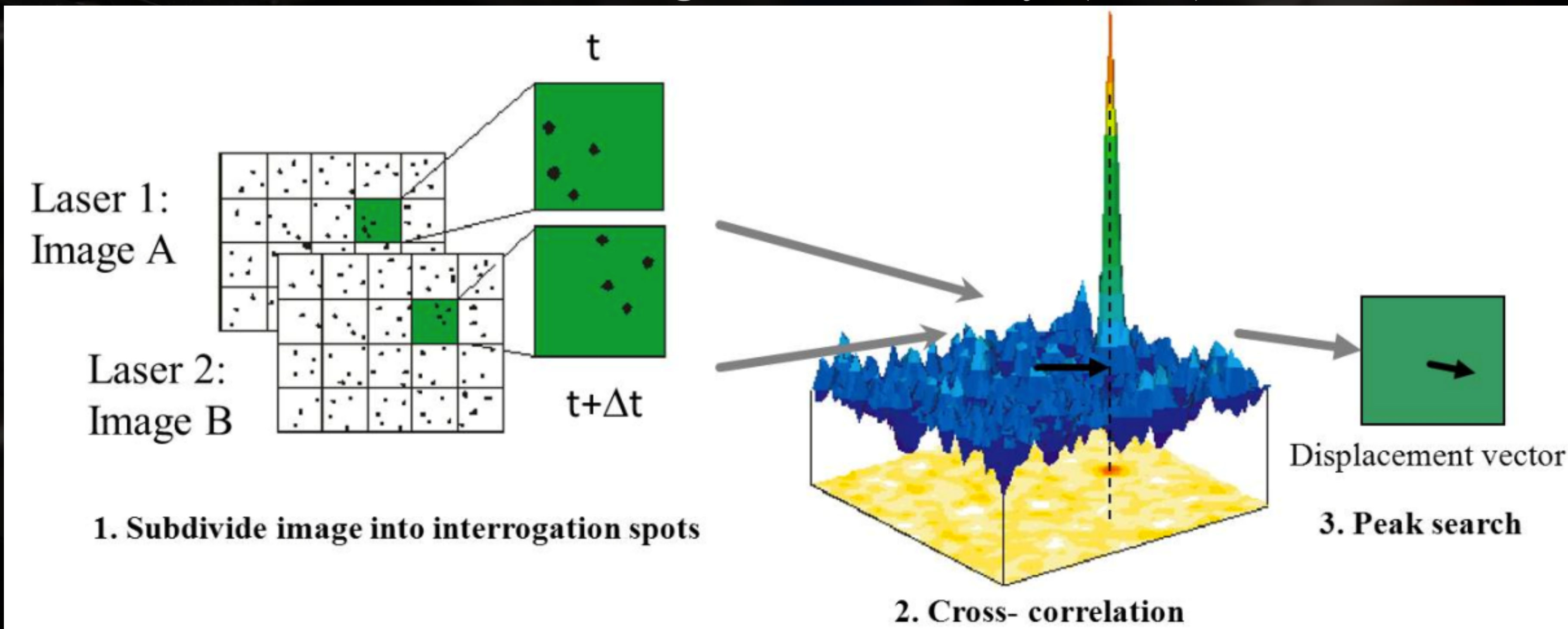
Peter A. Cocks, Vaidyanathan Sankaran, and Marios C. Soteriou, AIAA SciTech Forum, 52nd Aerospace Sciences Meeting (2014)
DOI: 10.2514/6.2014-0826

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)



http://cav.safl.umn.edu/Facilities/piv.htm

Why laser diagnostics?

Laser spectroscopy

Spectrum

- Line frequency
- Line intensity
- Line width

speed
pressure
concentration
temperature

Spectrum can be related to the thermodynamic state of the gas

species

N_2 O_2 H_2 CO_2 H_2O

radicals

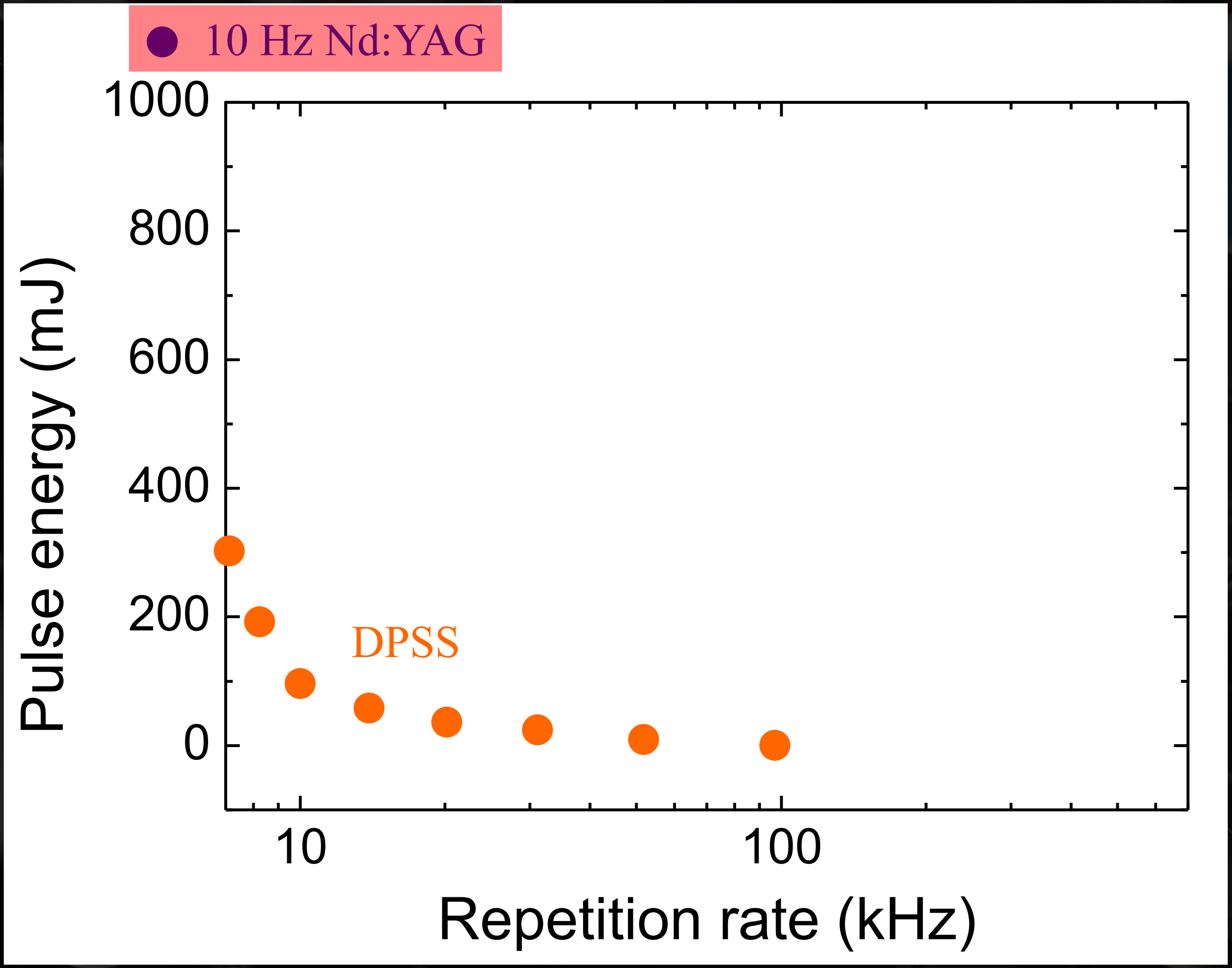
OH C_2 CH CH_2O

pollutants

NO CO

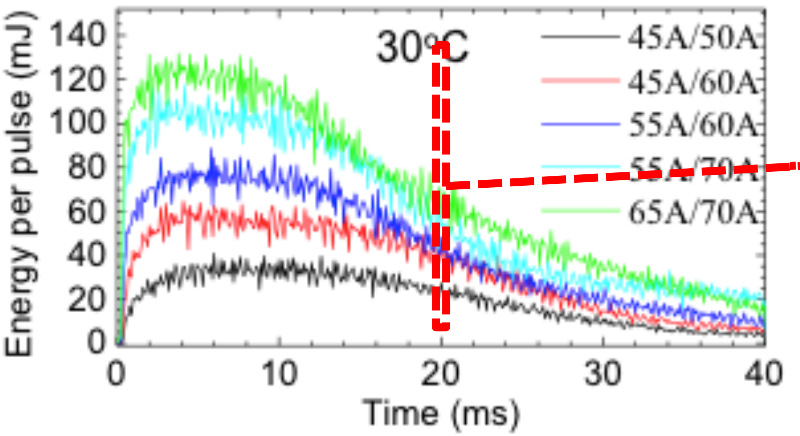
Pulse-burst laser layout

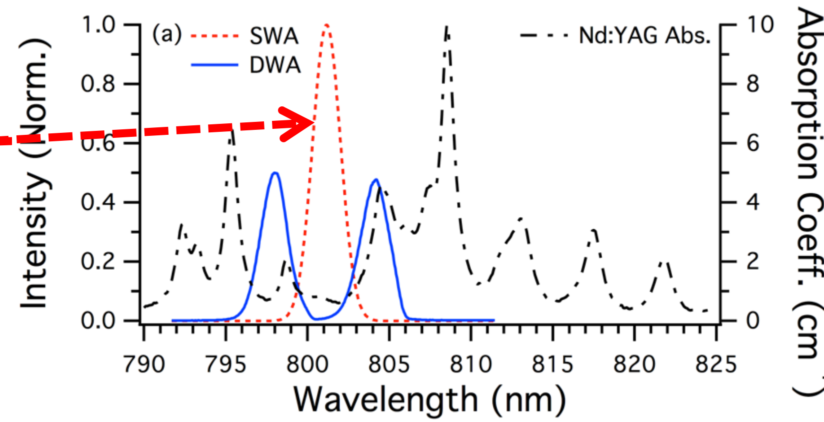
Burst-mode: high-energy output



Diode pumping: 100-ms Burst Duration

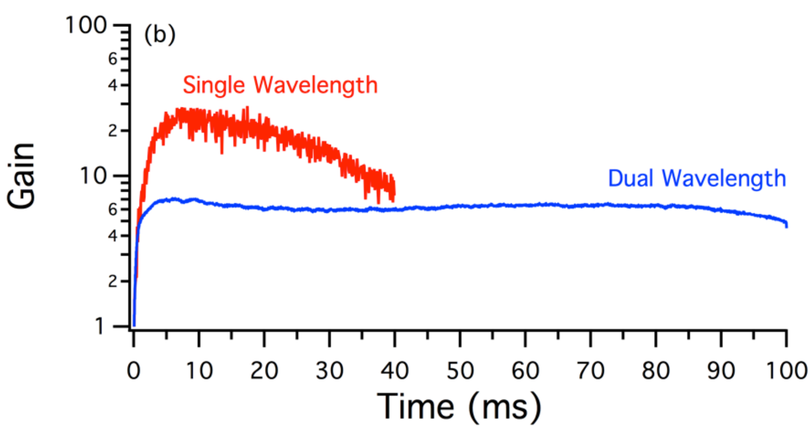
Diode array split for enhanced overlap



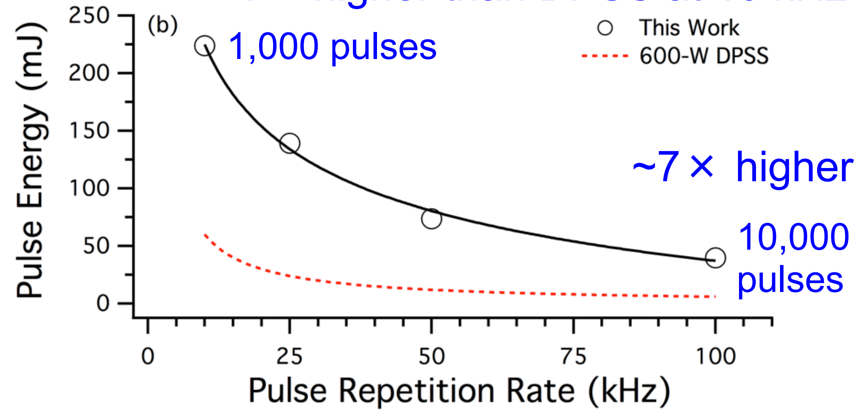


Slipchenko, Opt. Express (2013)

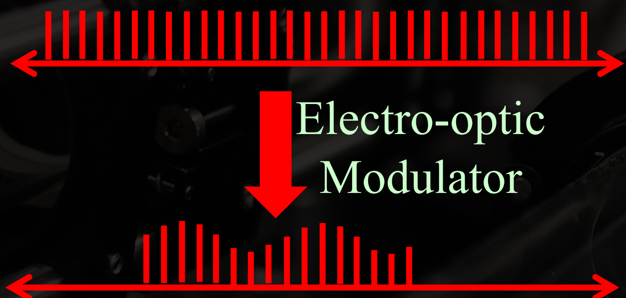
Slipchenko, Opt. Lett. (2014)

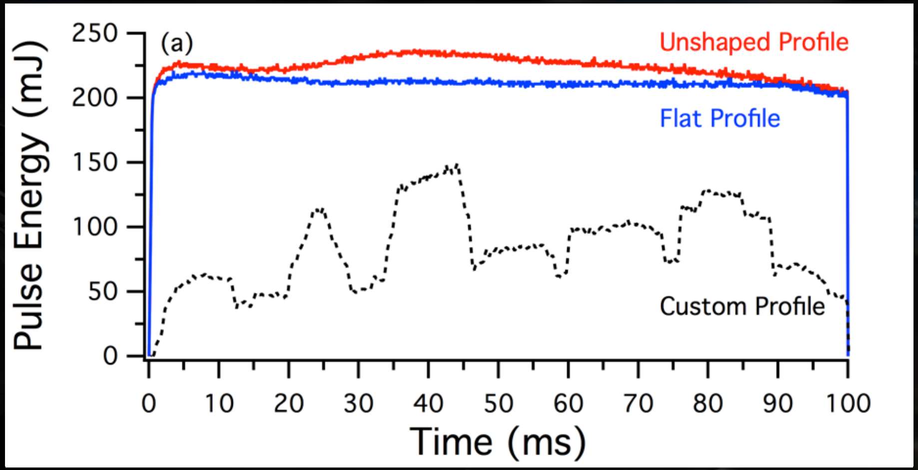


~4 × higher than DPSS at 10 kHz



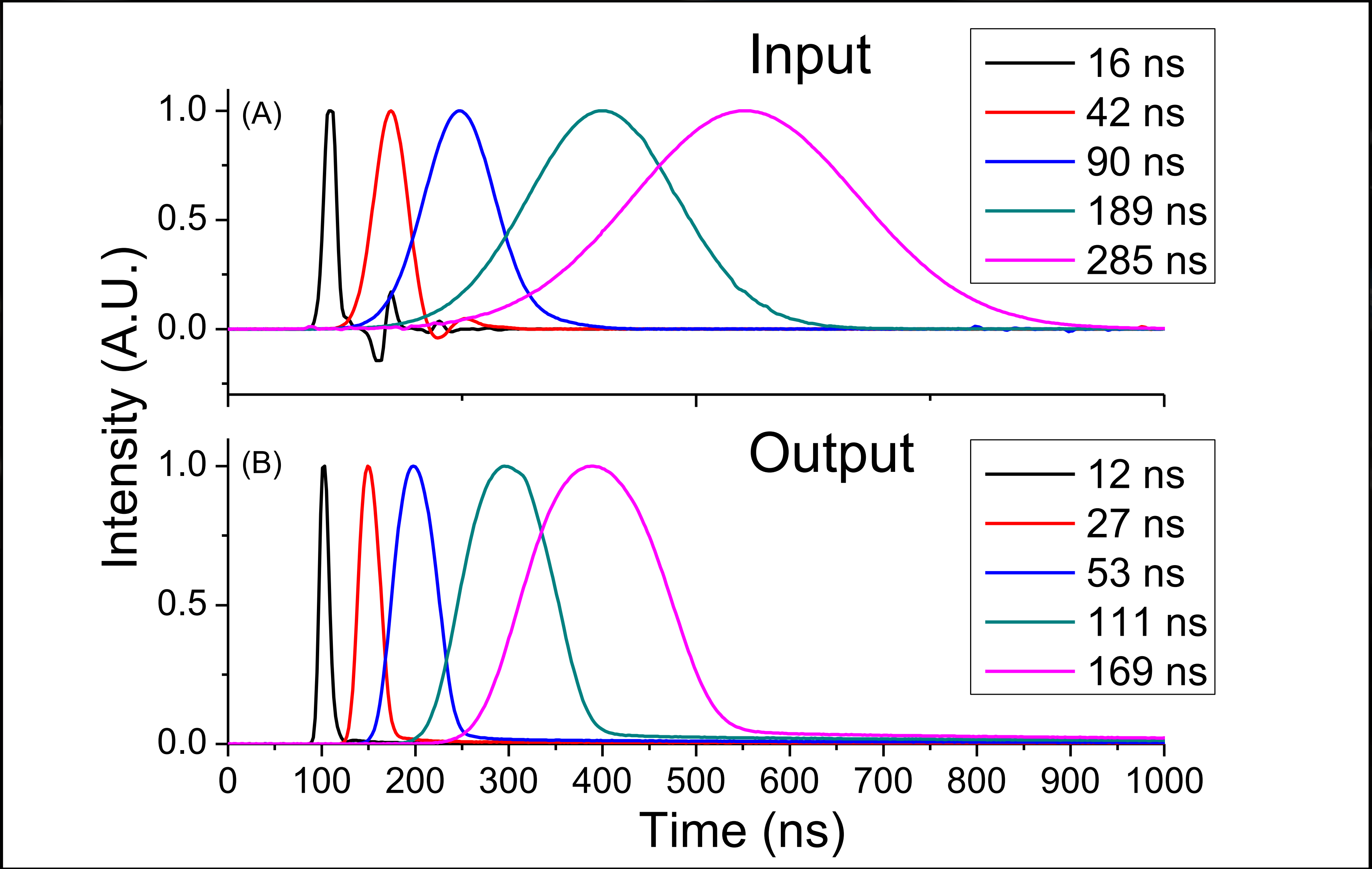
Pulse-burst laser flexibility



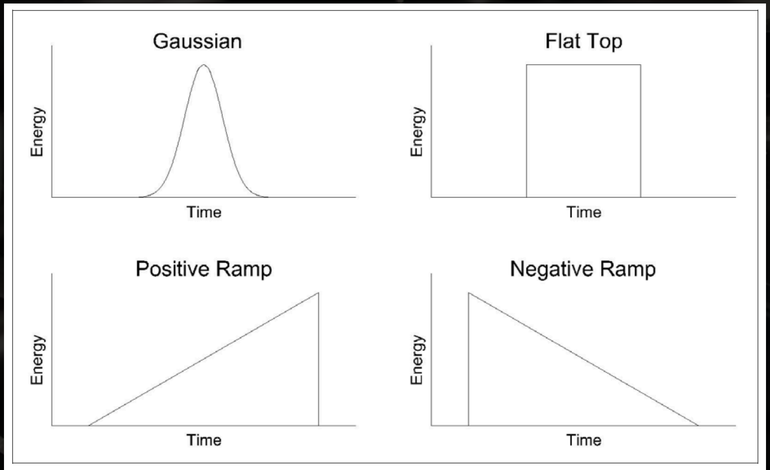


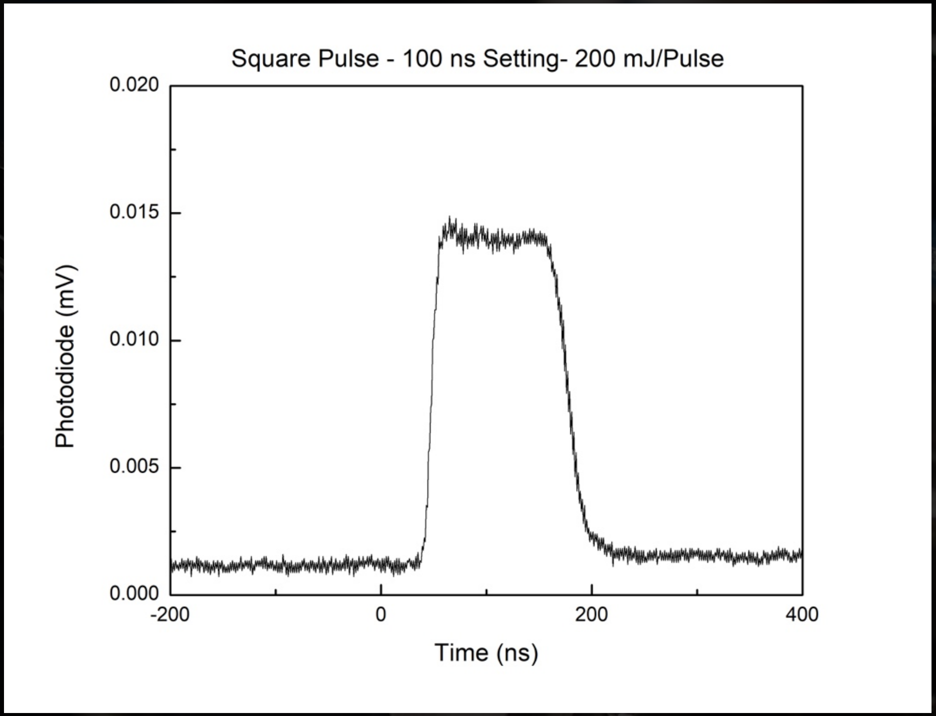
Pulse sequence shaping at high-repetition-rates via modulation of master oscillator

Flexible oscillator: Pulse Shaping

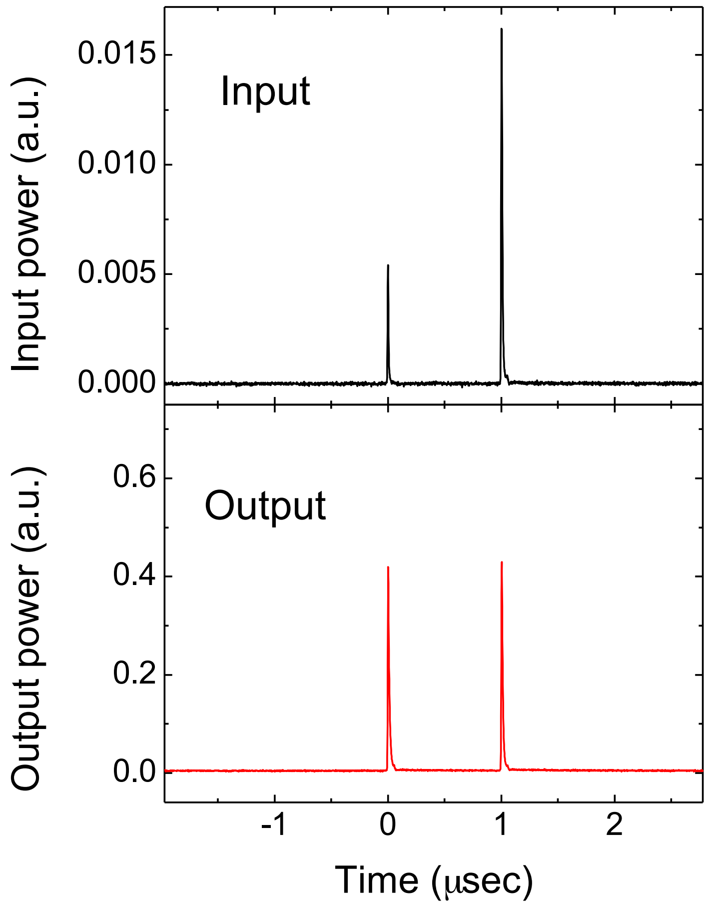


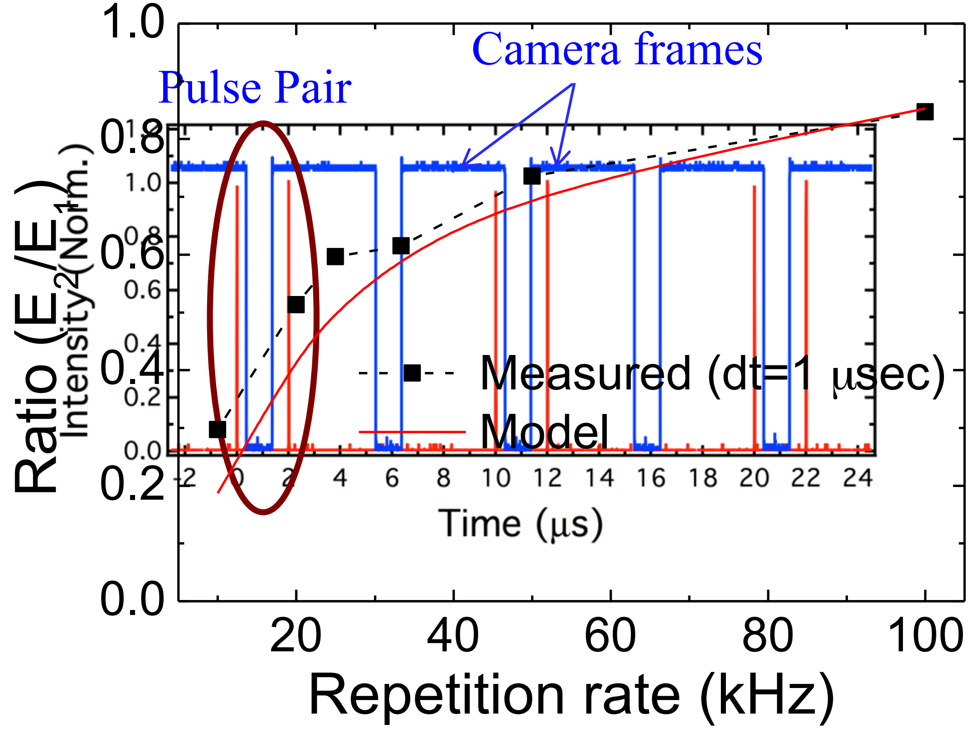
Flexible oscillator: Pulse Shaping





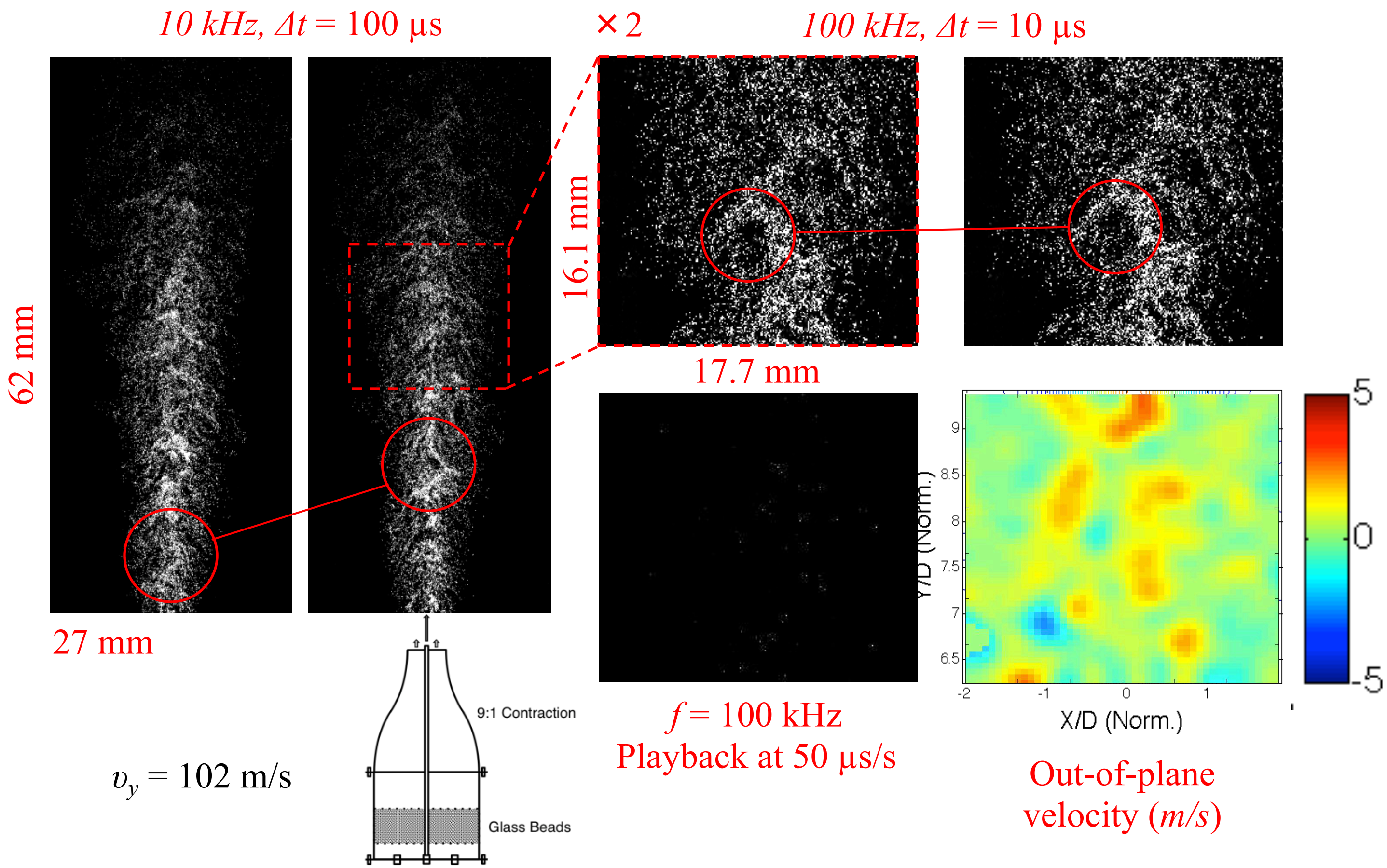
Flexible oscillator: Dual-pulse operation





10,000-frame, 100-kHz Stereo TR-PIV

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

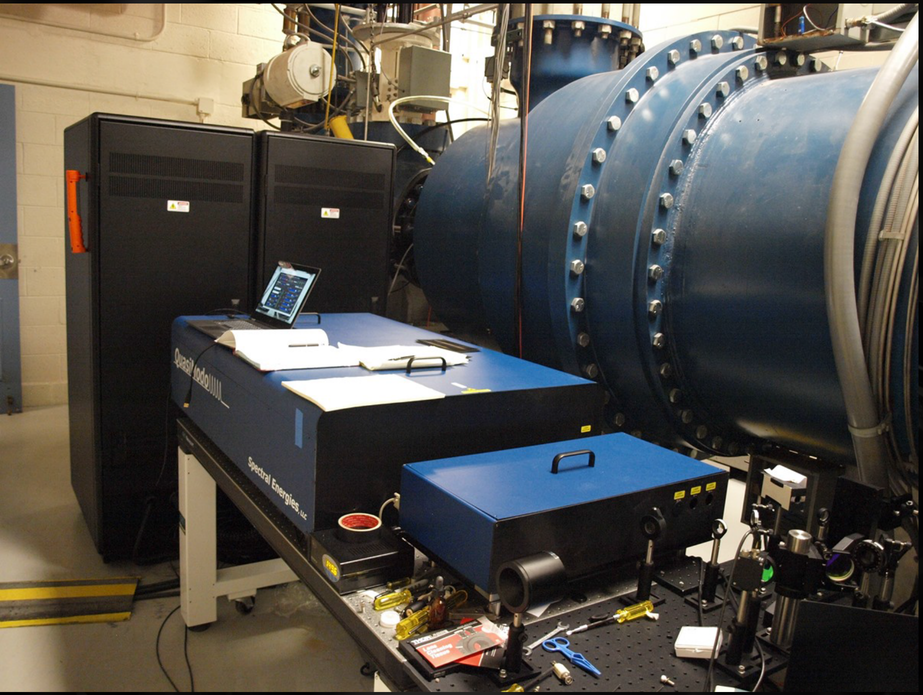


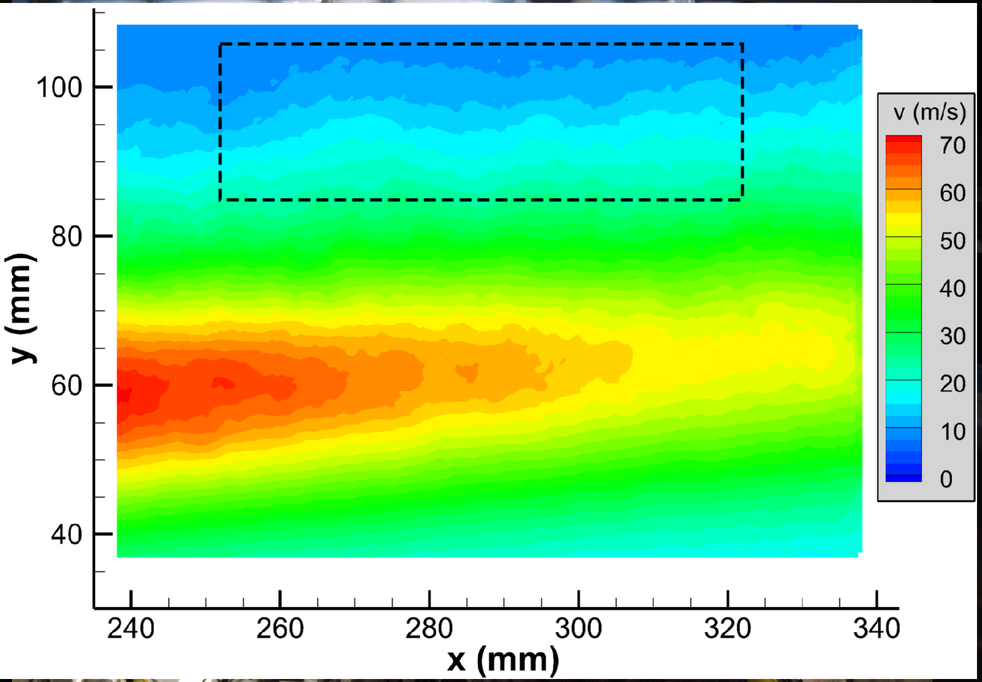
Stereo PIV along centerline of a Mach 0.3 free jet with Re = 30,000.
Up to 4 mJ per pulse at 100 kHz with 1 µs inter-pulse spacing.

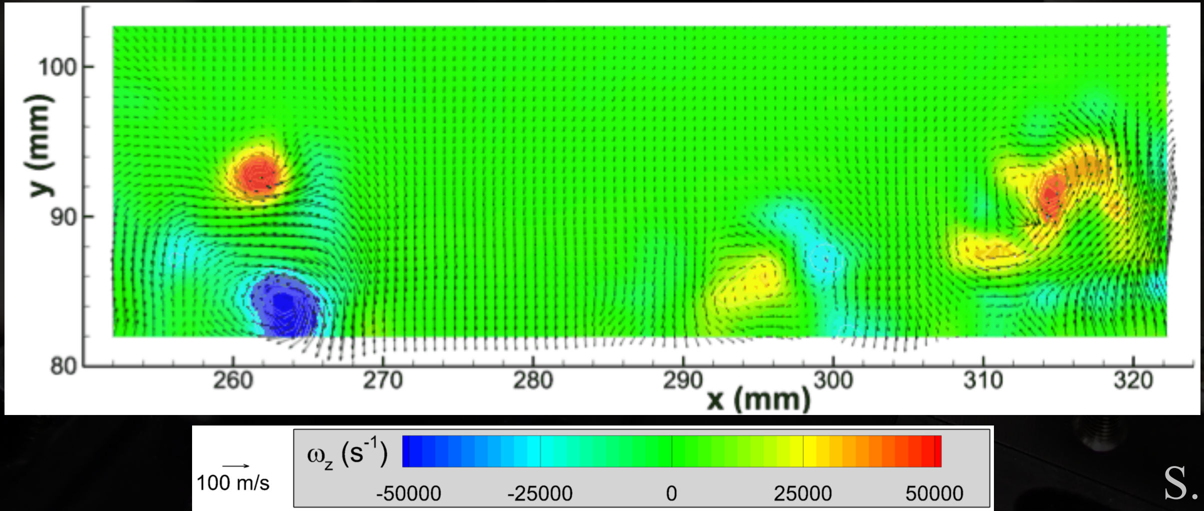
Miller et. al. 2015

25 and 50 kHz TR-PIV in Trisonic Wind Tunnel

Mach 3.7 jet issuing into a Mach 0.8 crossflow

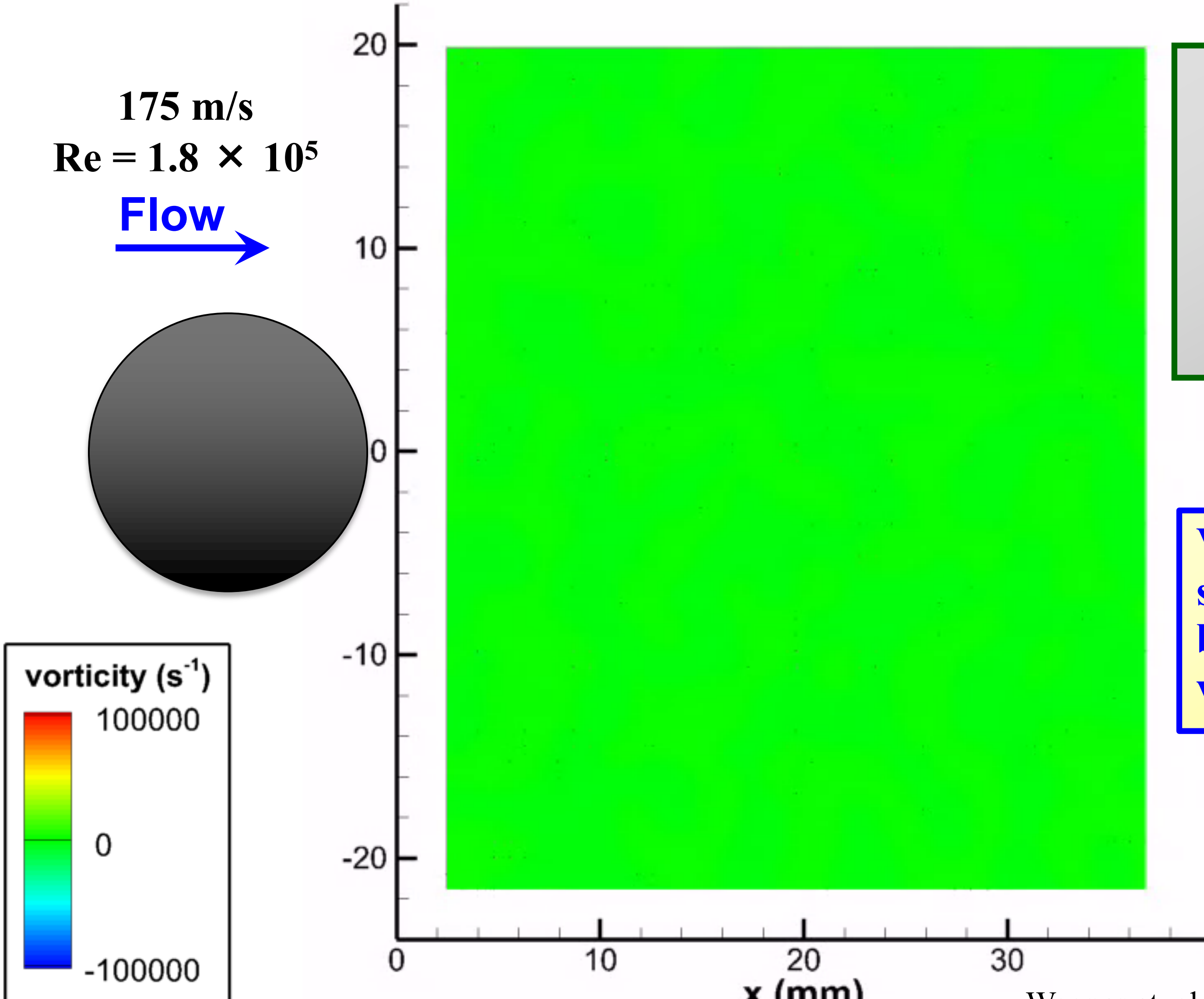






S. Beresh et. al. 2015

Transient Wake Vorticity Behind Cylinder



50 kHz pulse pairs

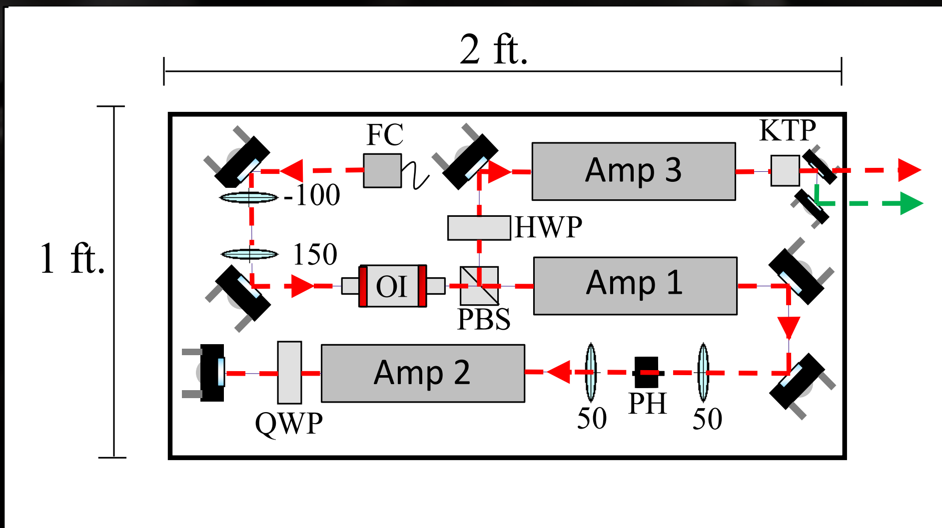
20 mJ/pulse @532nm

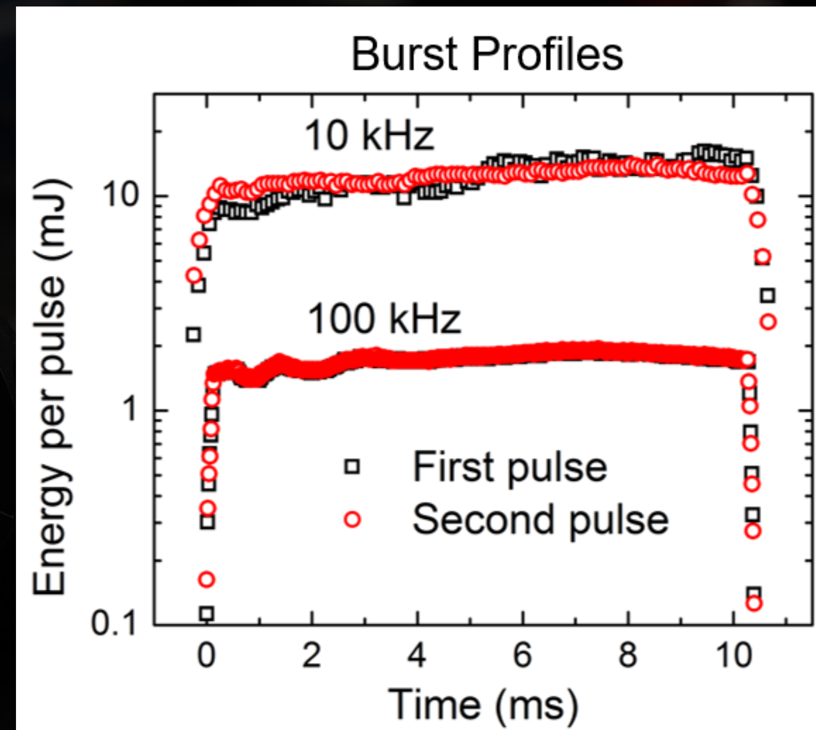
Final interrogation window: 24 × 24 pix (1.8 × 1.8 mm²)

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

Wagner et. al., 2016 doi:10.2514/6.2016-0791

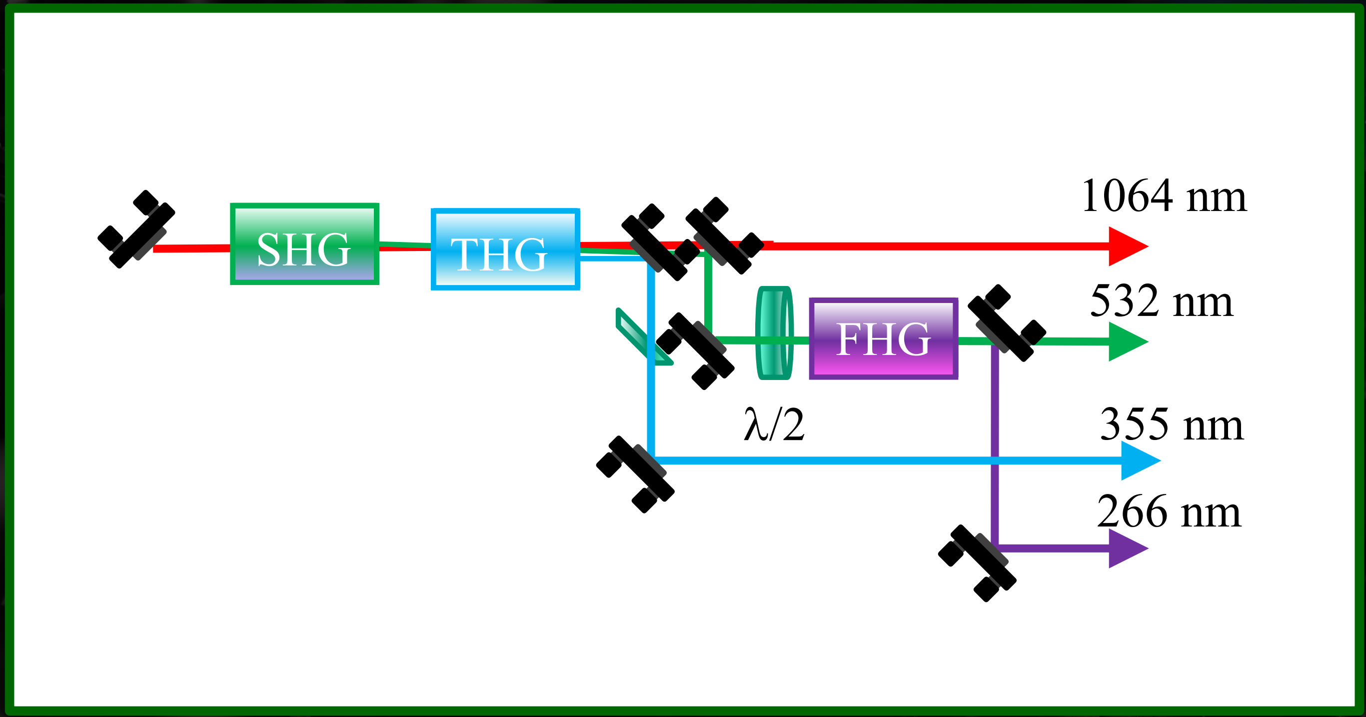
Development of a compact 14 J Nd:YAG burst-mode laser for PIV





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

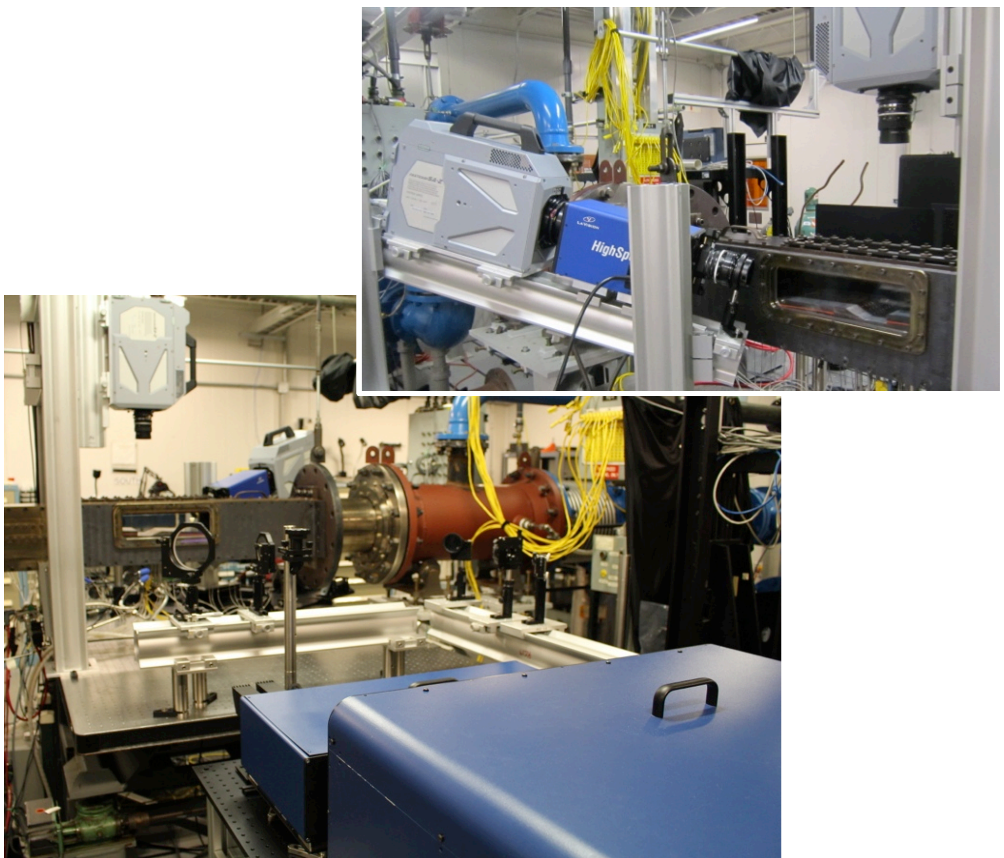
Higher Harmonics

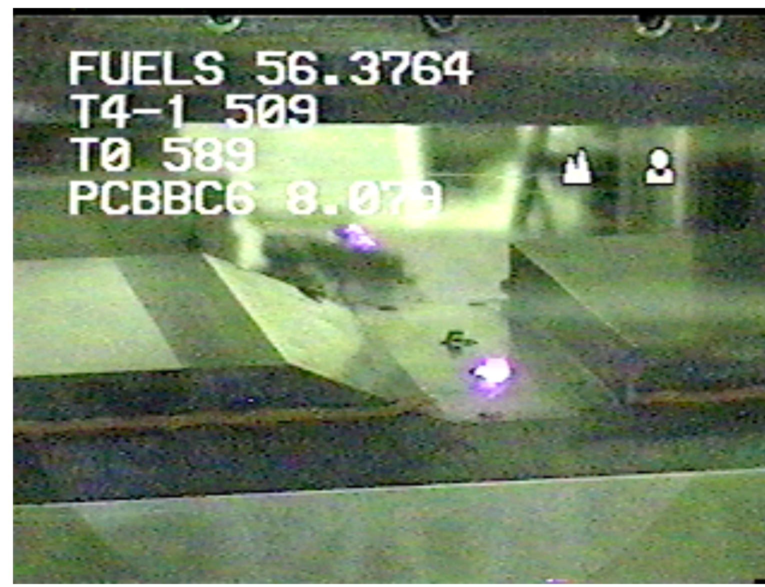


50 and 100 kHz formaldehyde PLIF

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

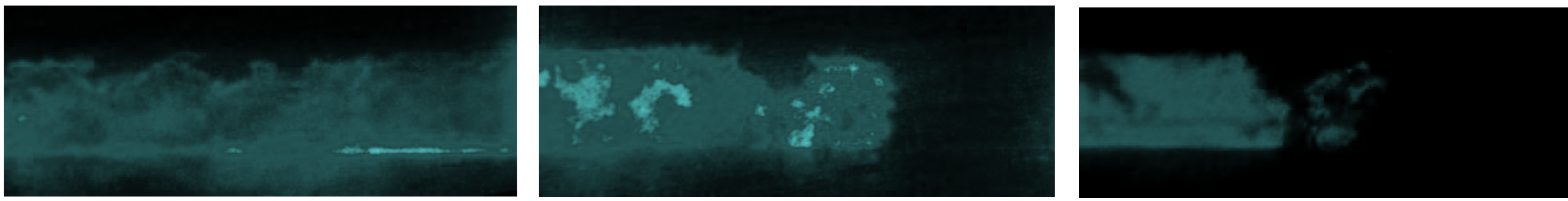
50 and 100 kHz formaldehyde PLIF

Mach 2 scramjet flameholder

Formaldehyde PLIF and Chemiluminescence

50 kHz, 75 SLPM C_2H_4

Side camera PLIF



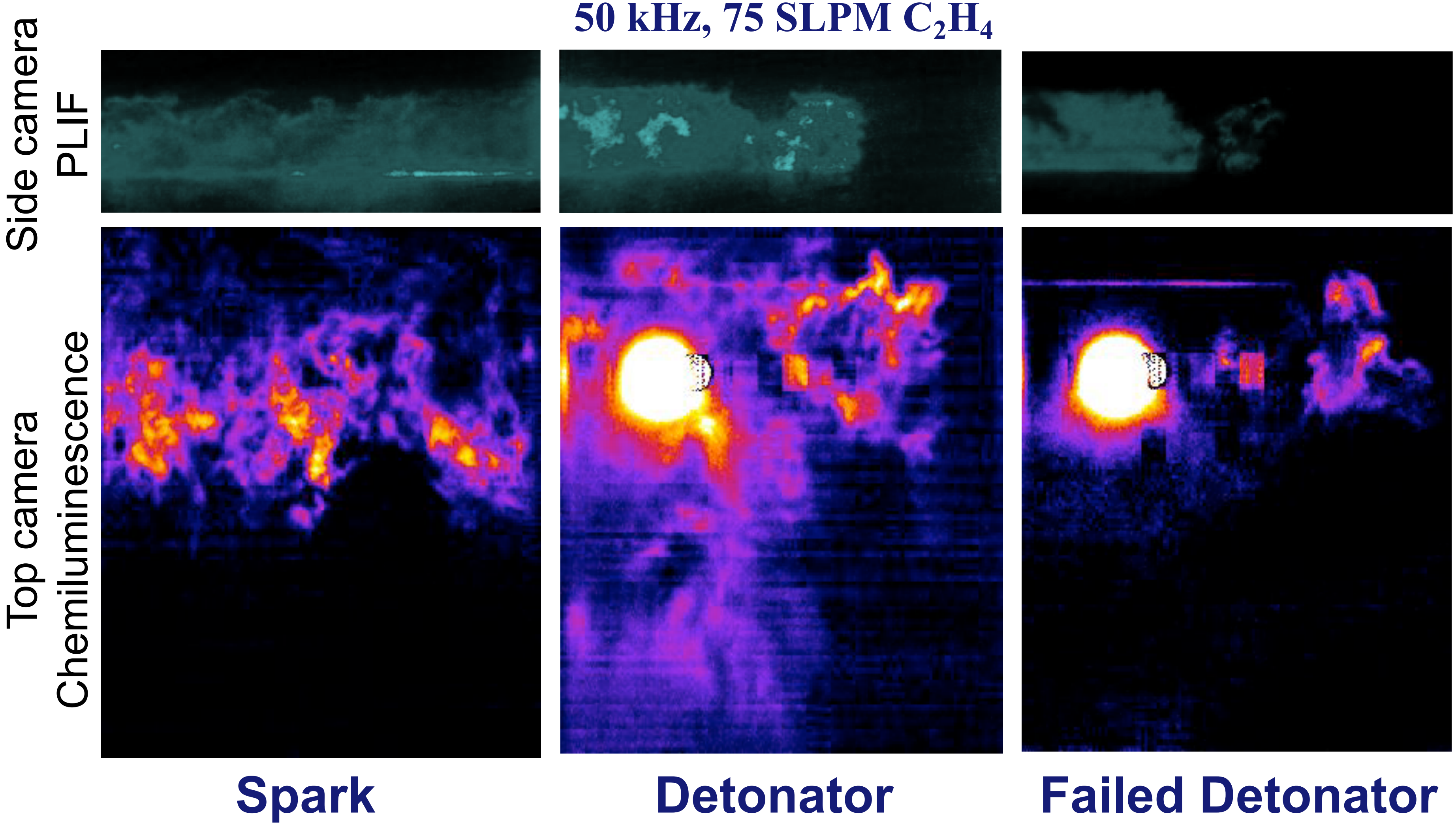
Spark **Detonator** **Failed Detonator**

50 and 100 kHz formaldehyde PLIF

Mach 2 scramjet flameholder

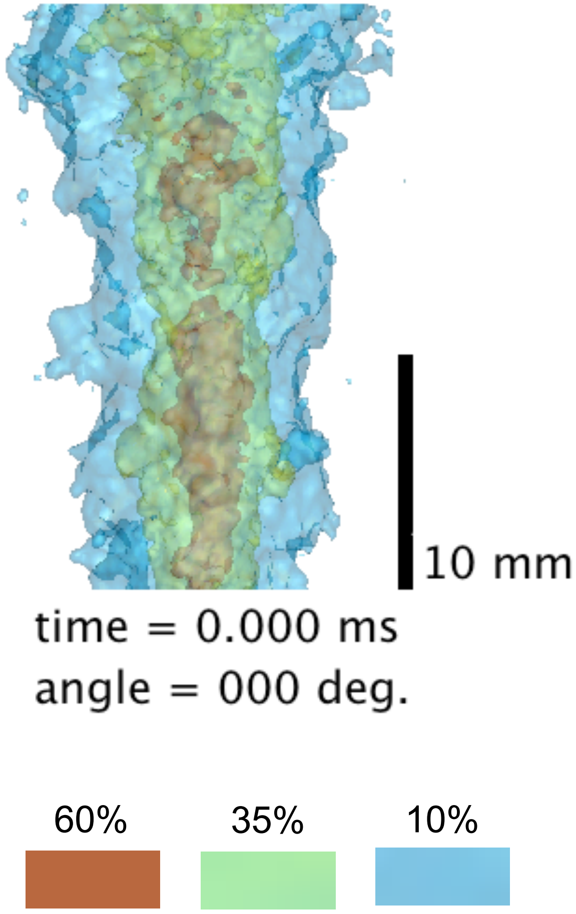
Formaldehyde PLIF and Chemiluminescence

50 kHz, 75 SLPM C_2H_4



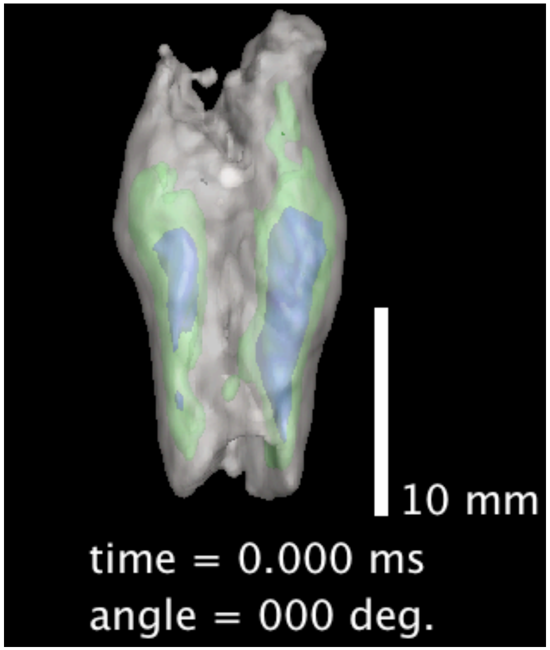
High-Speed 3D Combustion Species Measurements

20-kHz Tomo
Acetone LIF



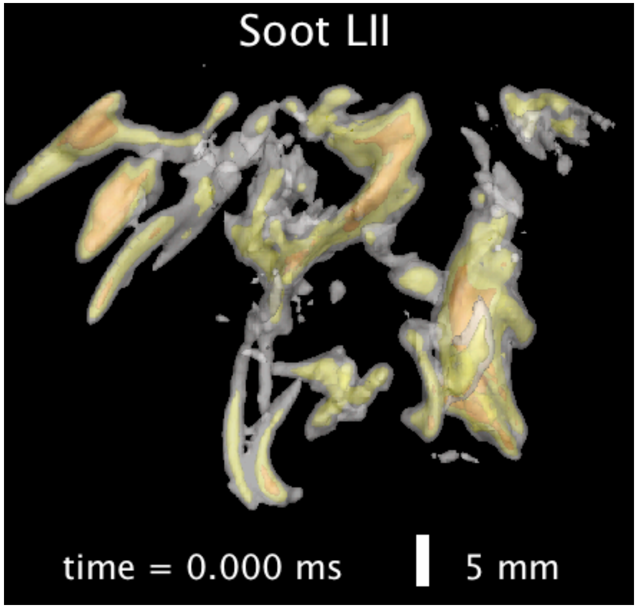
Halls et al, Proceedings of the Combustion Institute 36 (3), 4611-4618 (2017)

20 kHz Tomo
CH_2O LIF



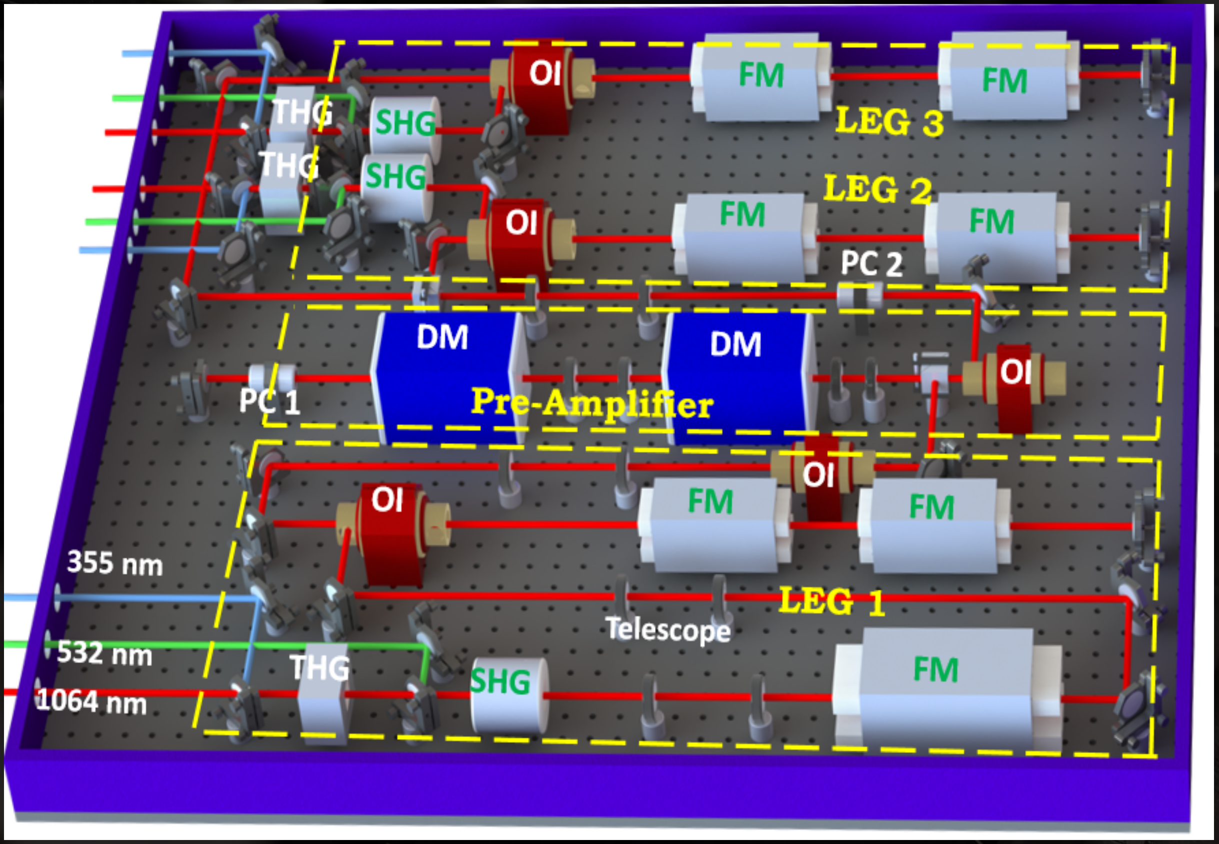
Halls et al. Optics letters 42 (14), 2830-2833 (2017)

10 kHz Tomo LII

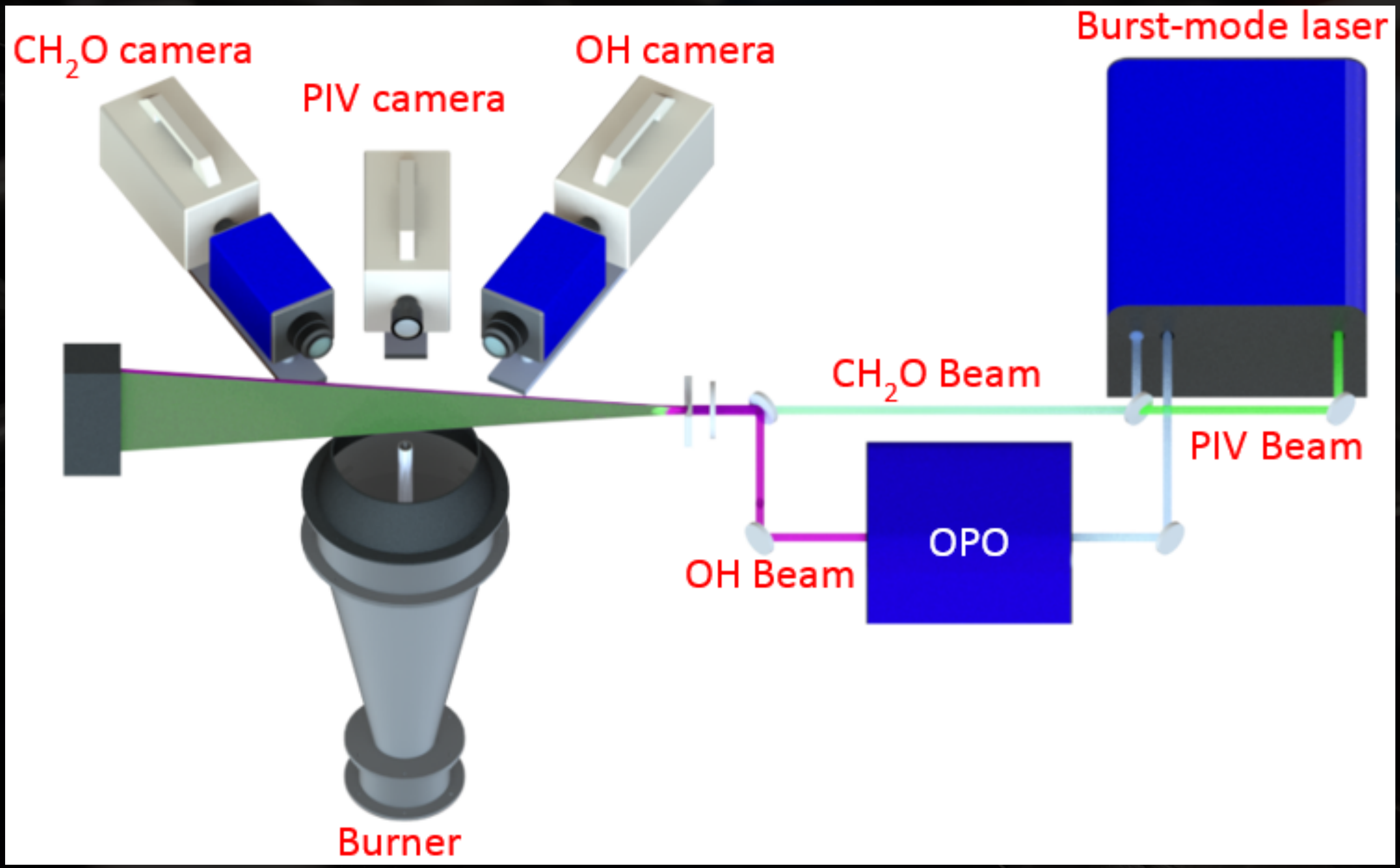


Meyer et al., Optics express 24 (26), 29547-29555 (2016)

Multi-Leg Burst Mode Laser

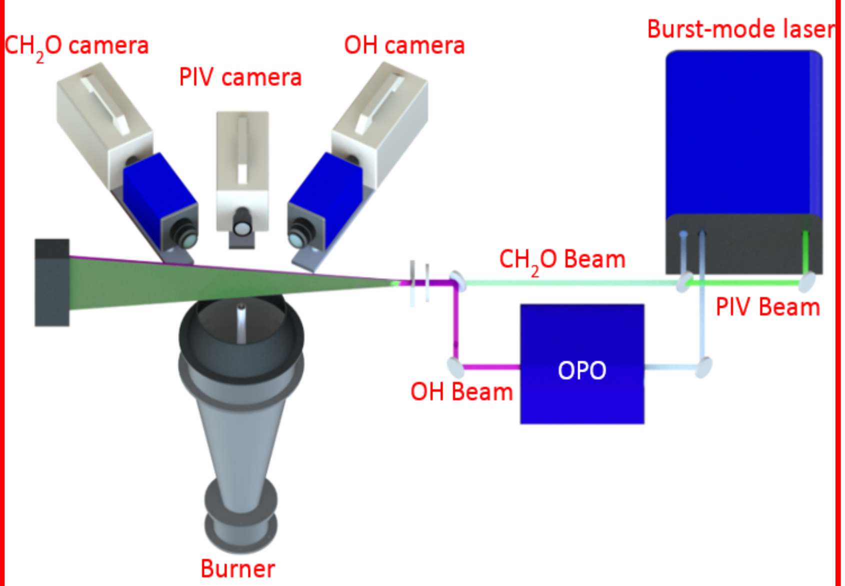


Multi-Leg Burst Mode Laser

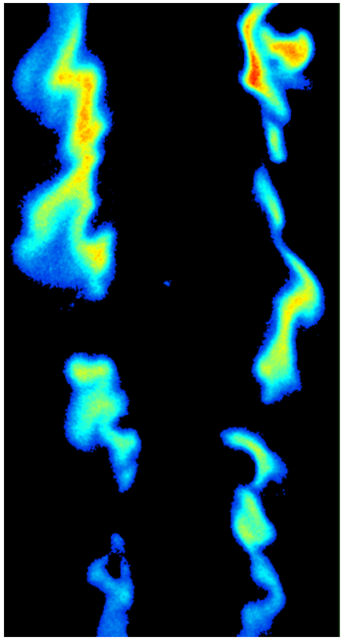


Roy et al Opt. Lett. **43**, 2704-2707 (2018)

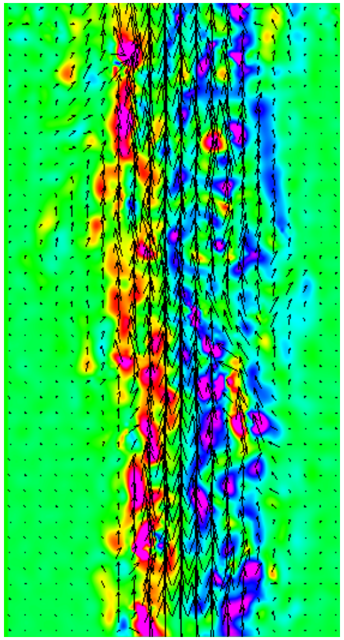
Simultaneous Measurements of Velocity and Scalars in Reacting Flows at 10 kHz



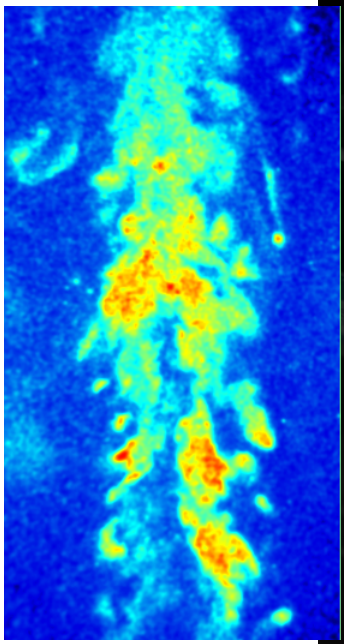
- OPO enabling wavelength tuning capability for OH LIF excitation
- Double pulse capability for PIV



OH PLIF



PIV



CH_2O PLIF

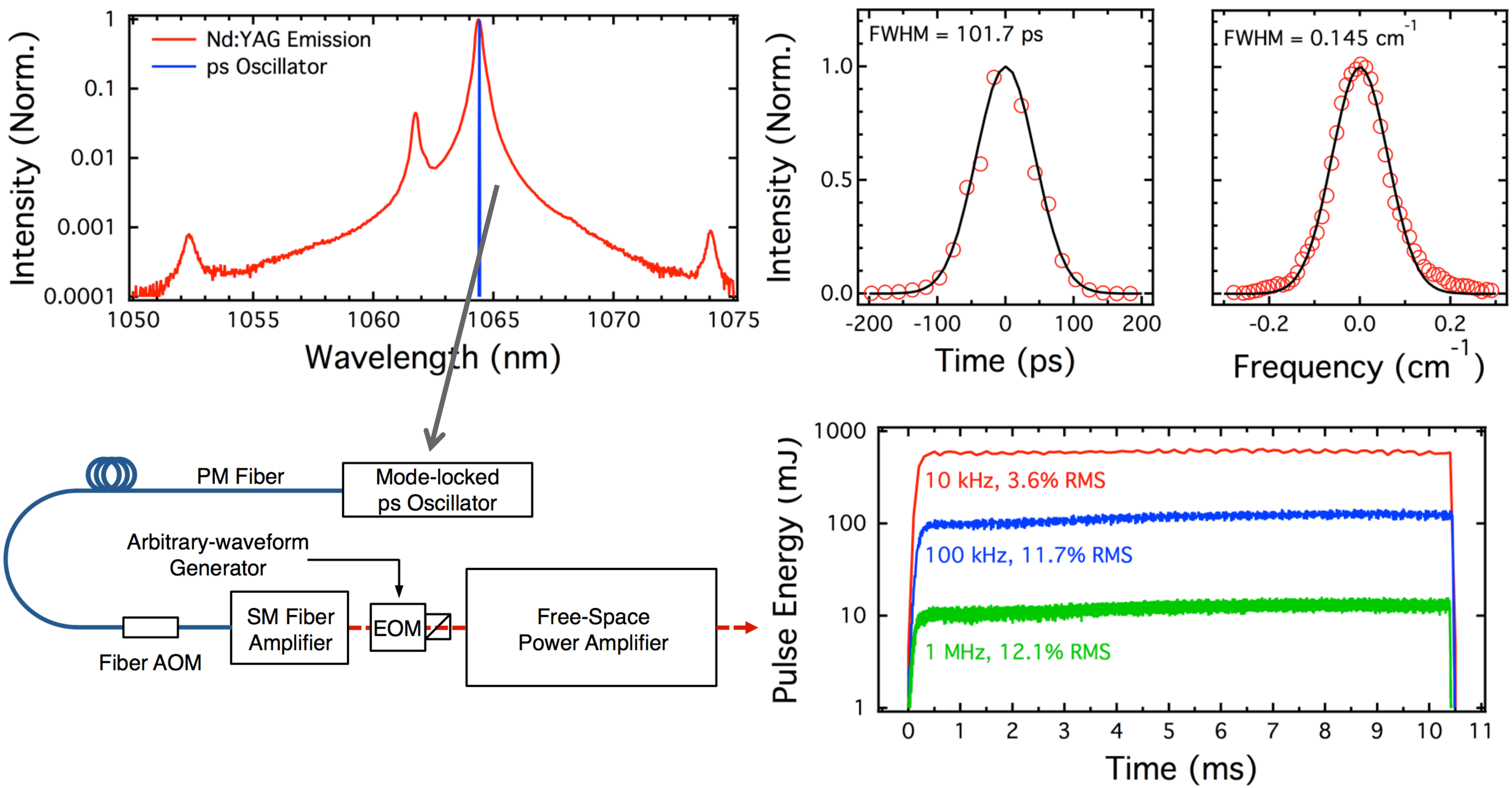
- **The unique laser system is capable of simultaneously measuring velocity and concentrations of OH and CH_2O at a rate of 10 kHz**

- **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)

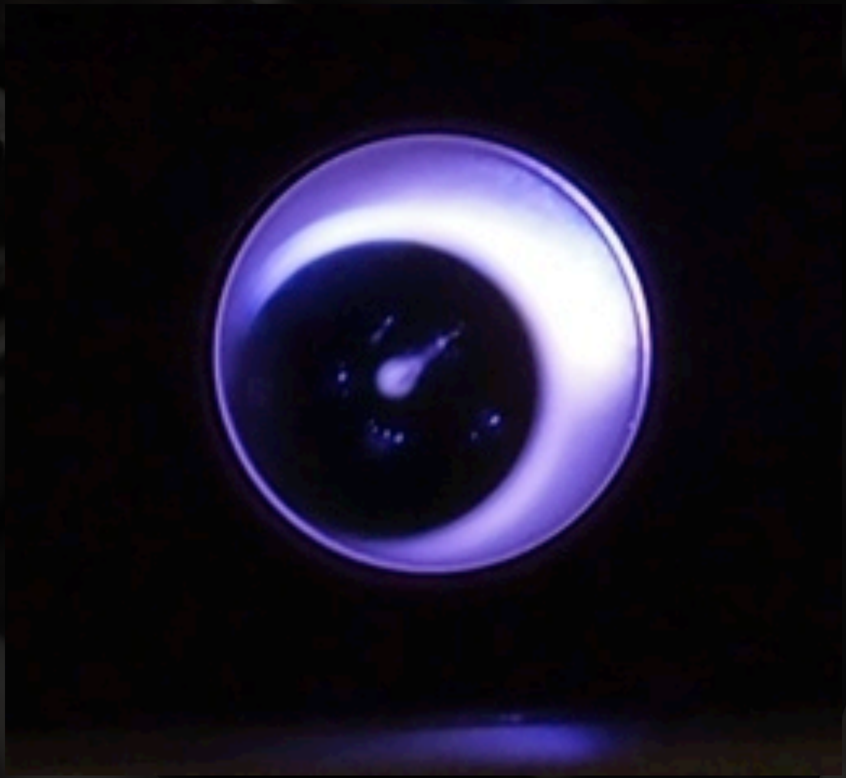
Picosecond Burst-mode Laser

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



S. Roy, J. Miller, N. Slipchenko et. al. Optics Lett. 2014

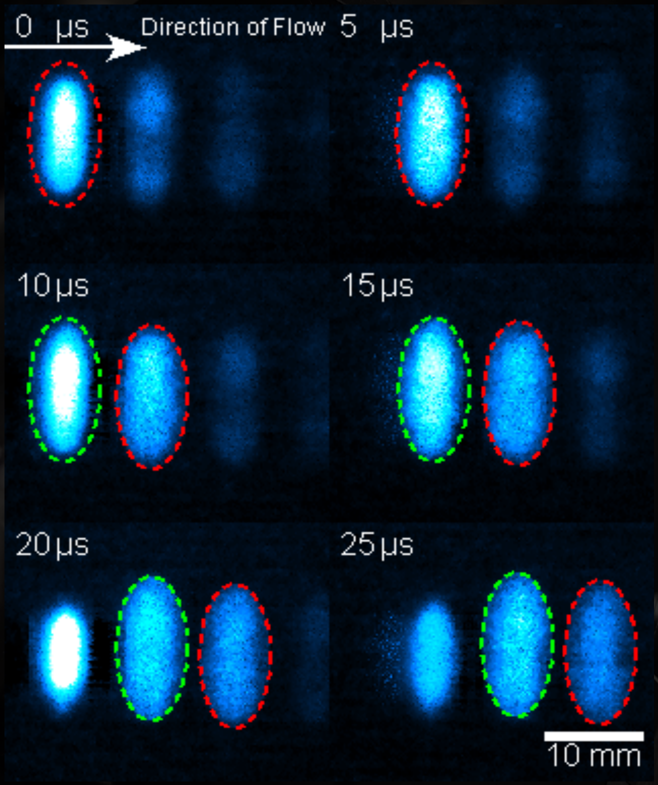
Picosecond Burst-mode Laser



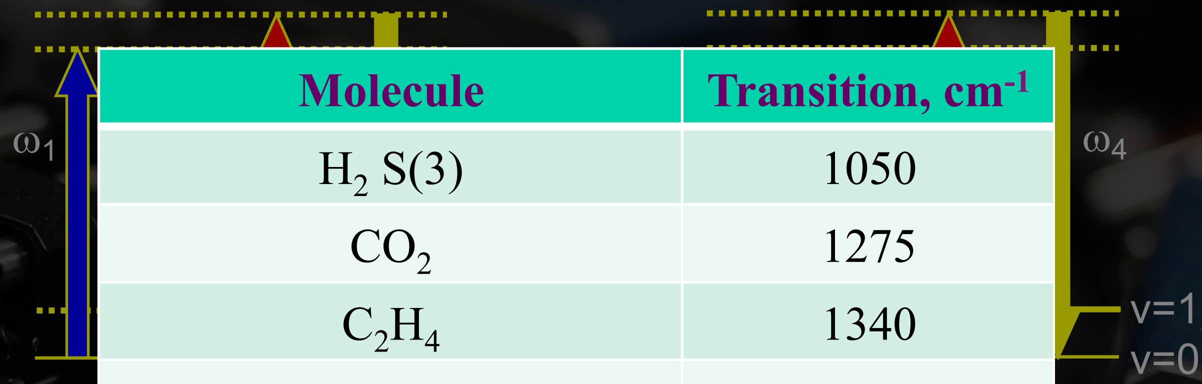
Self Focusing Damage to Nd:YAG Rod

Picosecond Burst-mode Laser

- Picosecond Laser Electronic-Excitation Tagging



Coherent anti-Stokes Raman scattering



Molecule	Transition, cm^{-1}
H_2 S(3)	1050
CO_2	1275
C_2H_4	1340
CO_2	1388
H_2 S(5)	1400
CH_4	1535
O_2	1555
C_2H_4	1625
H_2 S(6)	1650
CO	2143
N_2	2331
Hydrocarbons	2900 - 3200

The pump, ω_p, Sto… …l order polarization:

$$P^{(3)}_{CARS}(\omega_{aS} = \omega_p + \ldots \; \ldots_p)E(\omega_{pr})\left|E^*(\omega_S)\right.$$

where

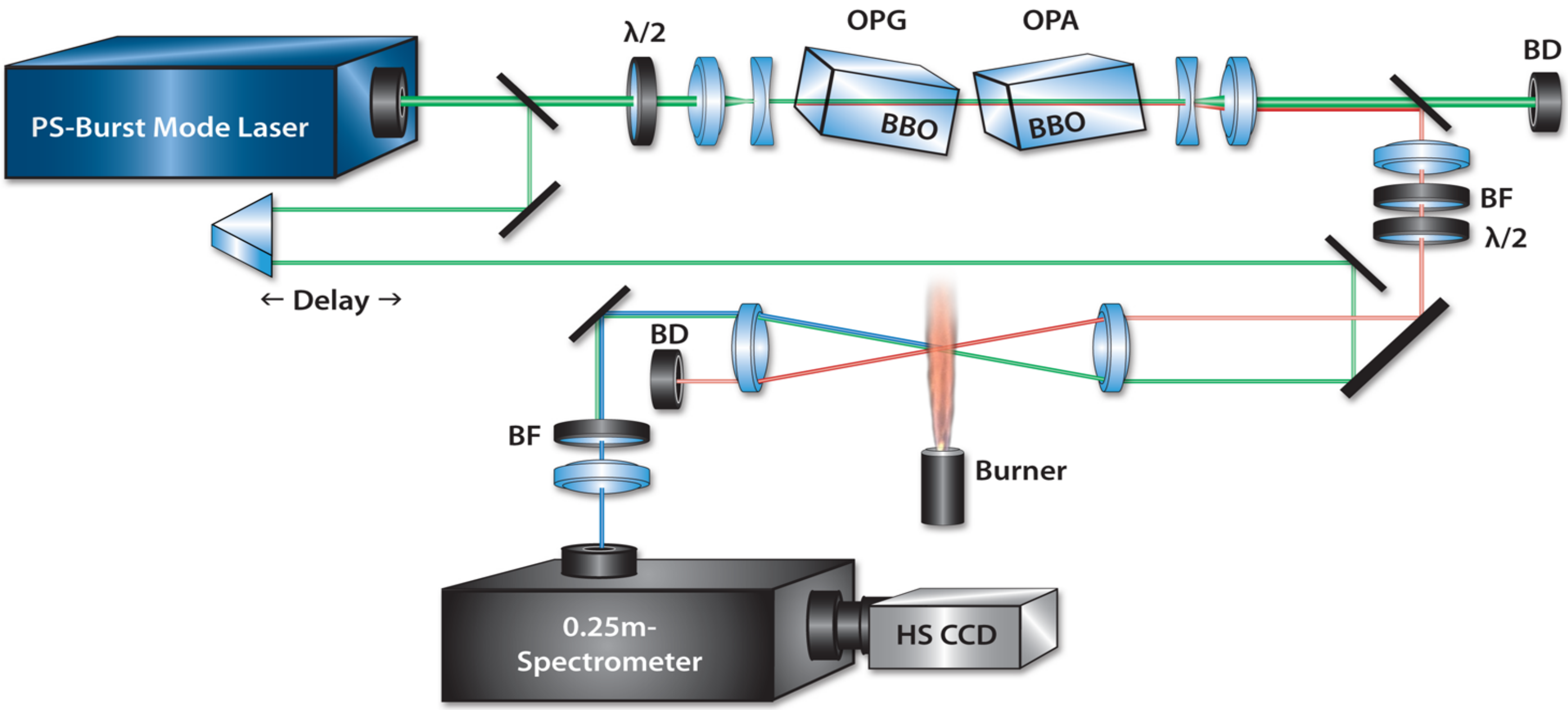
$$\chi^{(3)}_{eff} = \chi^{(3)}_{NR} \ldots$$

This polarizat…

$$I_{CARS}(\omega_{aS}) \propto N^2 \ldots$$

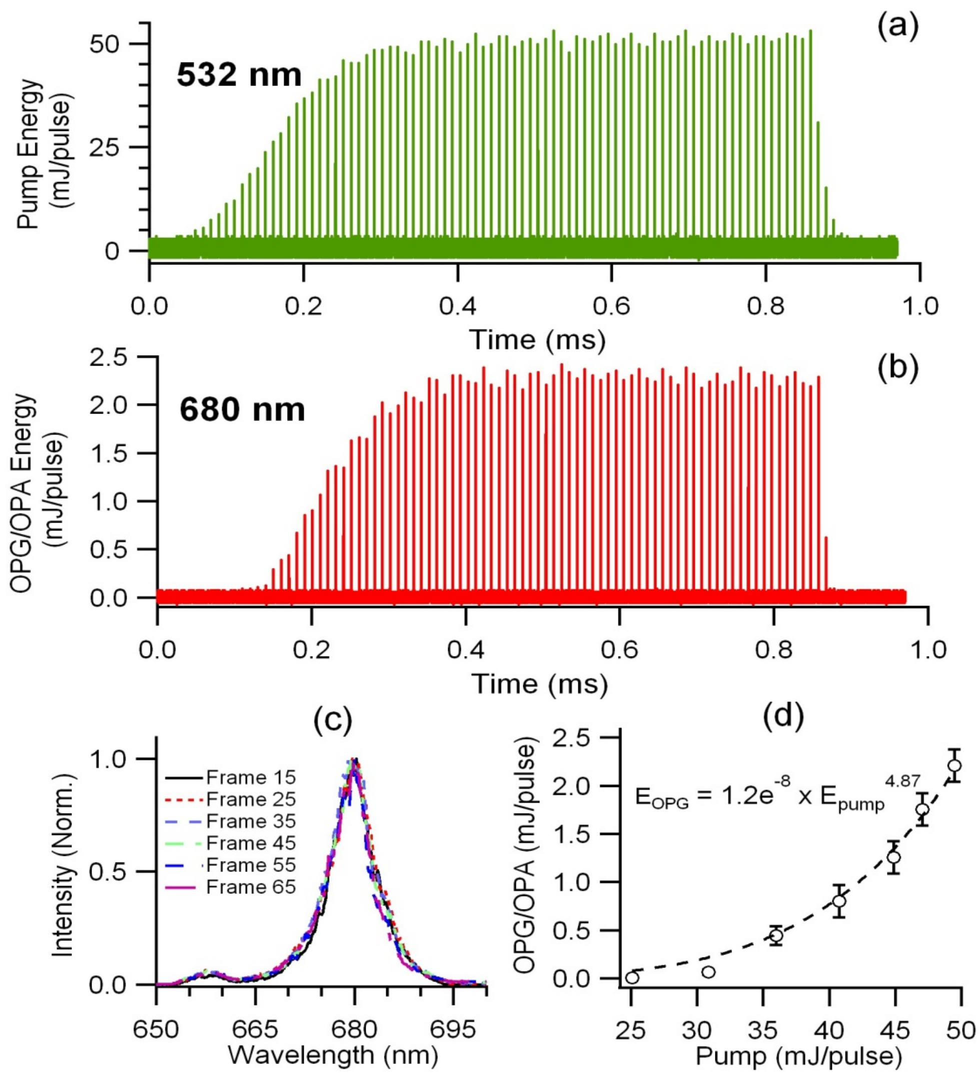
P. D. Maker and R. W. Terhune, Phys. Rev., 1965

100 kHz burst-mode CARS layout



Roy et. al. Optics Lett. (2016)

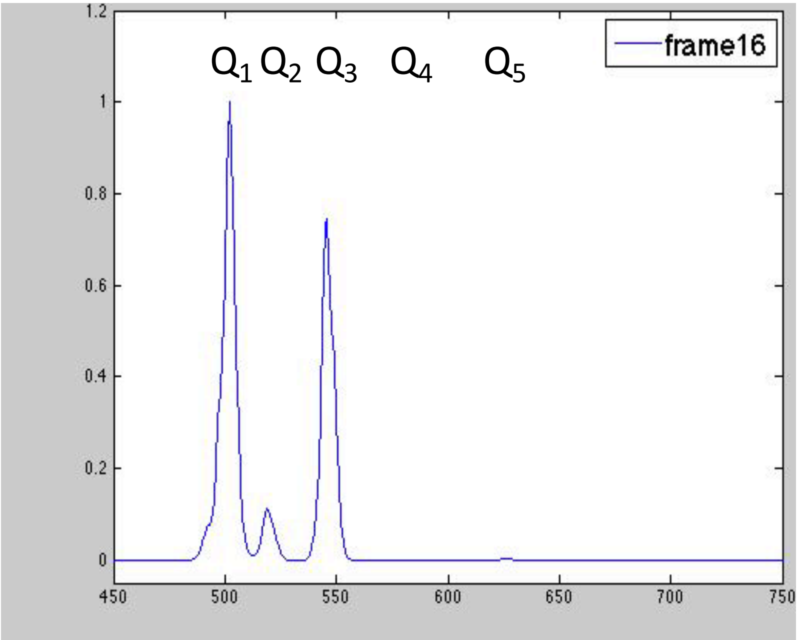
Burst-mode OPG/OPA performance

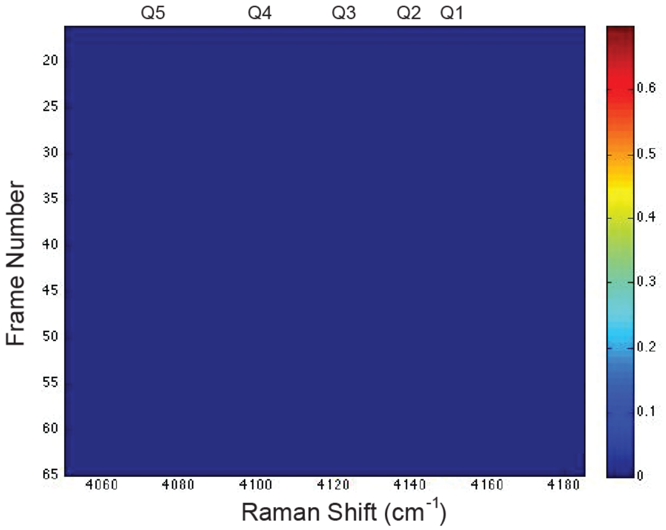


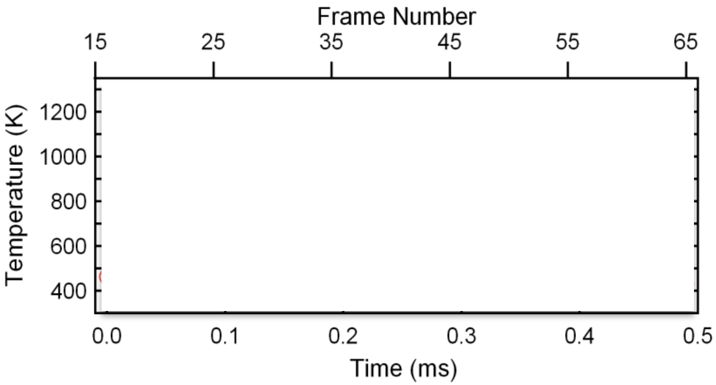
Roy et. al. Optics Lett. (2016)

100-kHz CARS H_2 thermometry

Jet diffusion flame
Re~10,000



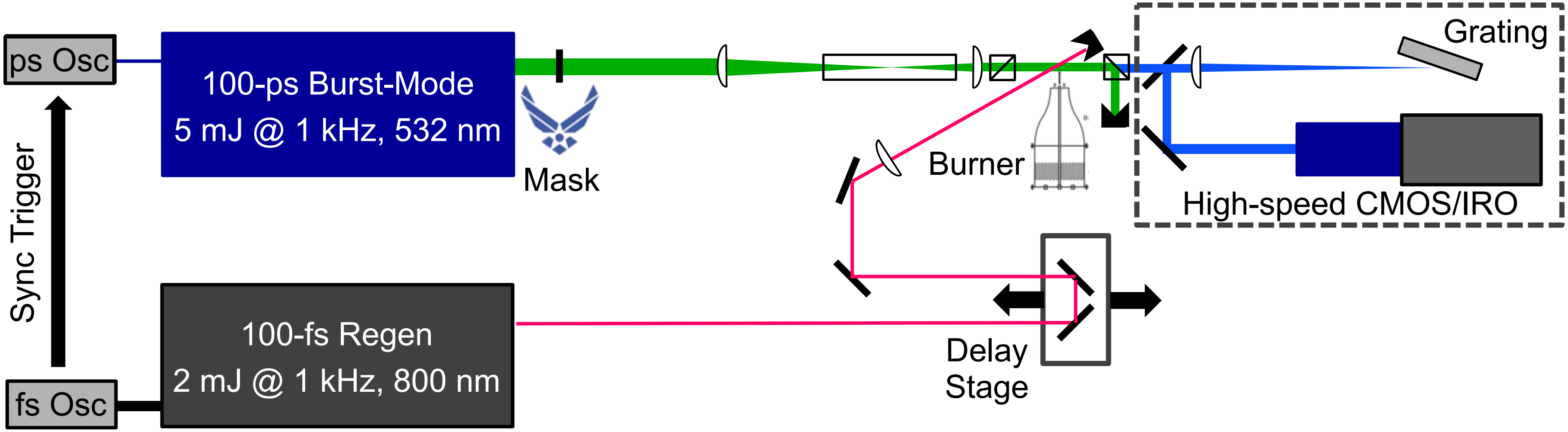


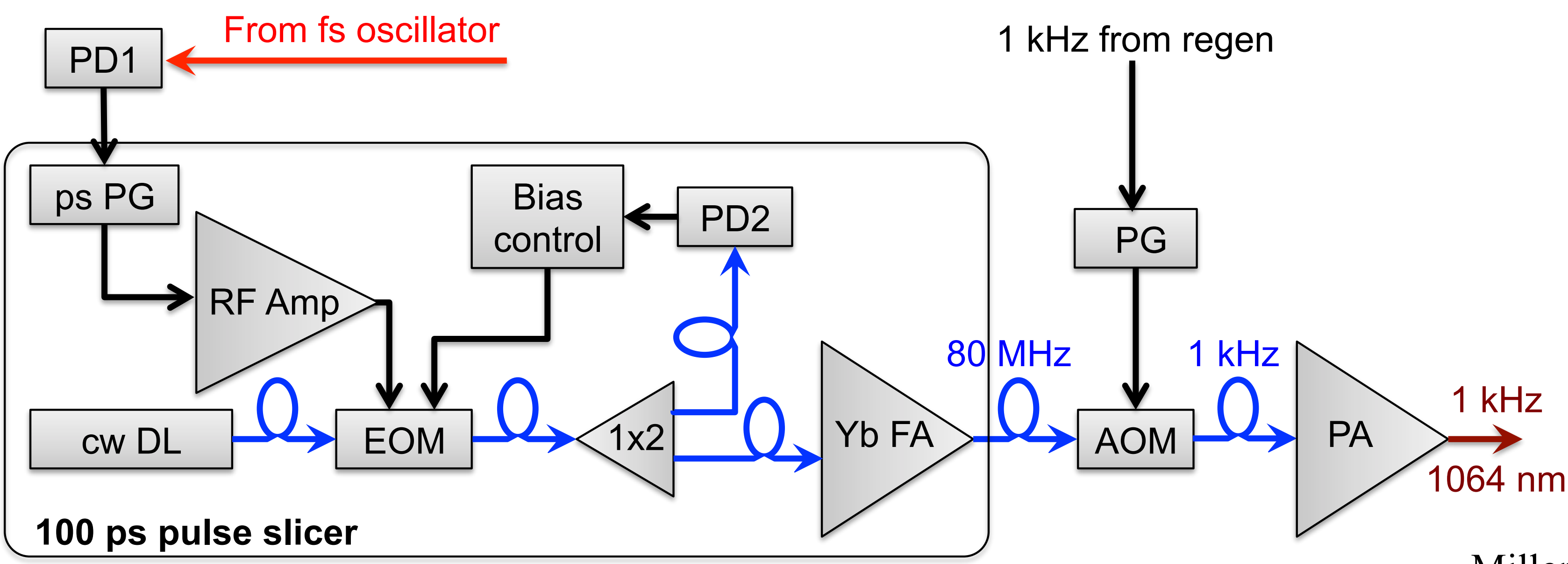


Captured dynamical change in temperature in highly turbulent flame at 100 kHz rate

Roy et. al. Optics Lett. (2016)

1-kHz Single-Shot 2D CARS



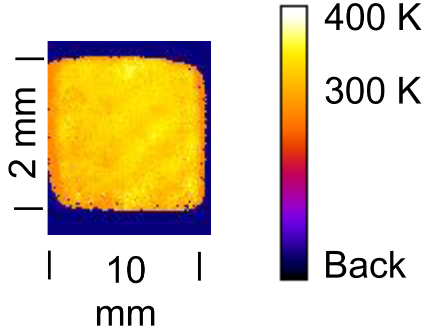


Miller (2016)

1 kHz Temperature Imaging in a High-Speed Heated Jet

Steady-State Temperature Analysis

T = 295 K	IRO Gain	T_{avg} [K], (%)	$T_{RMS,X}$ [K], (%)	$T_{RMS,t}$ [K], (%)
O_2	35%	287.2 (2.6%)	27.1 (9.4%)	7.4 (2.6%)



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

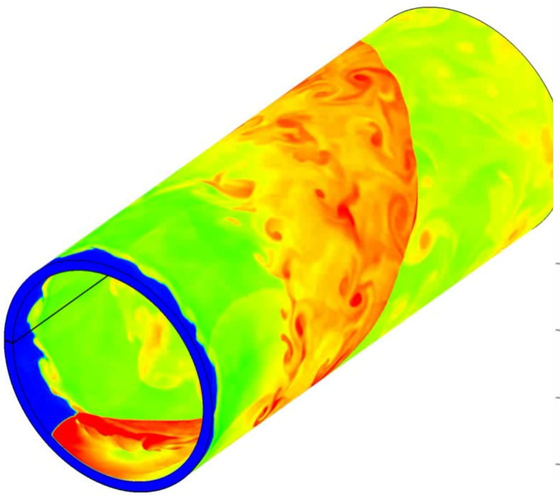
SYSTEM SPECS

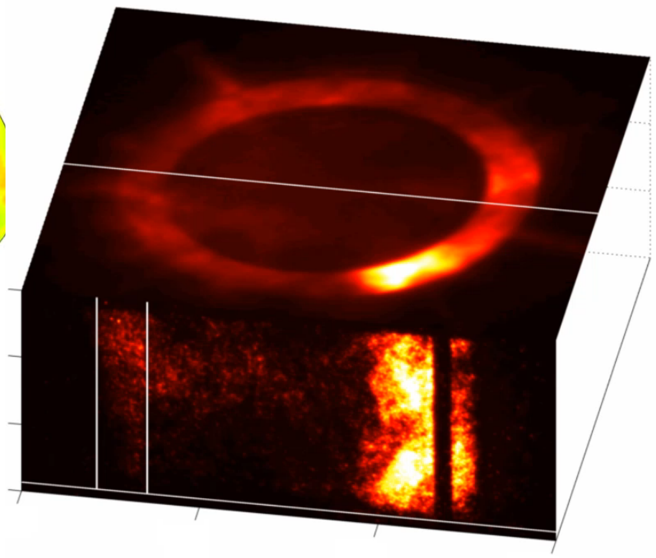
Quasimodo Model	1200	150	1500	100 ps option
Individual pulse width	10-15 ns	10-15 ns	10-15 ns	100 ps
Pulse frequency within a Burst	2-100 kHz	2-100 kHz	2-100 kHz	2-100 kHz
Number of pulses in Burst	100 @ 10 kHz	100 @ 10 kHz	100 @ 10 kHz	100 @ 10 kHz
	1000 @ 100 kHz	1000 @ 100 kHz	1000 @ 100 kHz	1000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

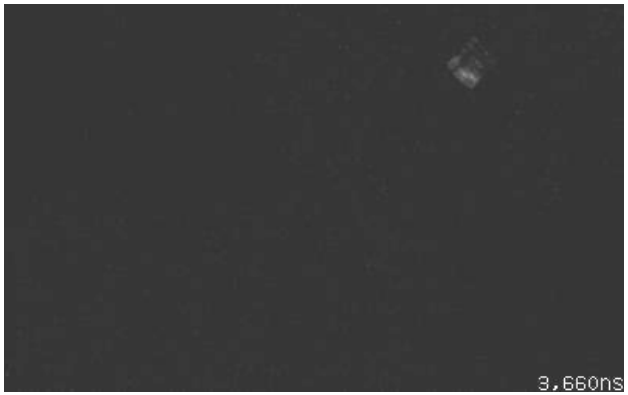
Outlook

- 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





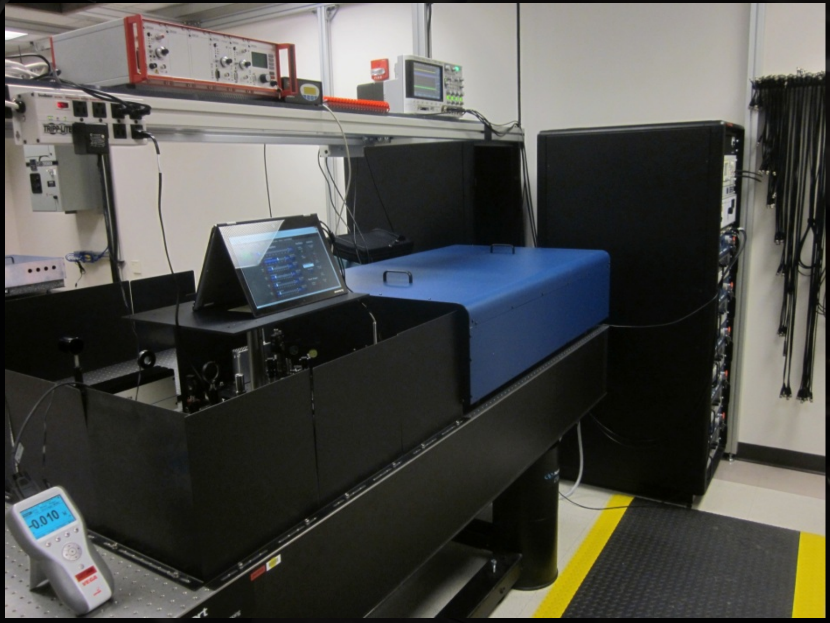


- Supersonic combustion wave, Mach > 7
- 4D cellular wave front structure, requiring **MHz** time resolution to track!
- Multiphase flows in explosives, particles of varying sizes, gas/solid phase velocities
- Most subsonic, supersonic, and high-speed systems

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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