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as of 02-Jan-2023

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**STEM Degrees:**

**STEM Participants:**

**Major Goals:** The goal of this project was to select and purchase a MHz rate pulse-burst laser to enable time-resolved measurements of various high-frequency flow properties.

**Accomplishments:** A DoD MHz rate pulse-burst was purchased for \$600,000.

**Training Opportunities:** Nothing to Report

**Results Dissemination:** Nothing to Report

**Honors and Awards:** Nothing to Report

**Protocol Activity Status:**

**Technology Transfer:** Nothing to Report

**PARTICIPANTS:**

**Participant Type:** PD/PI

**Participant:** Jesse Little

**Person Months Worked:** 1.00

**Funding Support:**

Project Contribution:

National Academy Member: N

**RPPR Final Report**  
as of 02-Jan-2023

**Partners**

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I certify that the information in the report is complete and accurate:

Signature: Jesse Little

Signature Date: 1/1/23 12:27AM

## **Final Report**

### **Pulse-Burst Laser for Highly-Resolved Flow Field Measurements in Both Space and Time W911NF2110284**

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**December 2022**

#### **1 Abstract**

DoD HBCU/MI program funds (\$600,000) have been used to purchase a MHz rate pulse-burst laser to enable time-resolved measurements of various high-frequency flow properties. This laser directly interfaces with existing high-speed cameras and related devices in the AME Department at UArizona enabling advanced flow measurements for fundamental research and computational model development and validation. The laser indirectly supports the research of over a dozen AME faculty members with four primary experimentalists (Profs. J. Little, S. Craig, J. Jacobs, and I. Wygnanski) covering low-speed to hypersonic flows. This equipment will also foster existing and new collaborations with UArizona faculty in other strong units (e.g., Optical Sciences) as well as minority-serving institutions across the American Southwest.

#### **2 Introduction**

Laser diagnostics have revolutionized experimental fluid dynamics over the last 30 years advancing from qualitative visualizations to quantitative measurements in space and time. However, there is a general tradeoff between space and time resolution as it relates to the measurement system. Conventional high-power Nd:YAG lasers suitable for spatially resolving flow fields over a reasonably large field of view generally operate near 10 Hz with 200-400 mJ/pulse. However, the dynamics of interest can occur at much higher frequencies ranging up to 1 MHz depending on the problem at hand. Consequently, experimentalists must rely on ensemble averages and/or conditional sampling to build up an understanding of turbulent and transitional flows. In some cases (e.g., hypersonic wind tunnels), the facility run-times are so short that discrete time-resolved surface measurements are the most reliable source of quantitative data. A MHz rate pulse-burst laser, along with DURIP-funded high-speed cameras and our existing hardware and software, removes these barriers allowing spatially and temporally resolved flow field measurements across a wide range of conditions including subsonic, transonic, supersonic and hypersonic, all of which are studied in the Turbulence and Flow Control Laboratory (TFCL) directed by the PI and in the AME Department at UArizona as a whole.

### 3 Equipment Description

Pulse burst lasers generate MHz rate output by slicing the signal of low power continuous lasers then passing the resulting beams through a series of pulsed Nd:YAG amplifiers (Thurow et al., 2013). Over the last 20 years, pulse burst lasers have progressed from specialized systems constructed of individual components arranged on large optical tables to packaged units with relatively compact footprints (e.g., 4.5ft x 2.5ft). The chosen supplier, Spectral Energies, LLC even offers rental units that can be transported across the country.

The system acquired here is a so-called standard 60 J, 532 nm burst mode laser. Specified pulse rates range from 5 kHz to 1 MHz with maximum burst rate of 0.1 Hz and selectable duration of 1, 2, 5 and 10 ms with longer bursts possible at decreased energy. A sample of available operating conditions is provided in Table 1. Note that double pulse operation supports inter doublet spacing of 100ns-1 $\mu$ s, 2 $\mu$ s, 5 $\mu$ s and 10 $\mu$ s at energy levels of 50% and >30% of 1064 nm and 532nm, respectively. Table 1 shows the flexibility of this system wherein pulse energies and frequencies can be optimized by tailoring the burst duration for a given flow field.

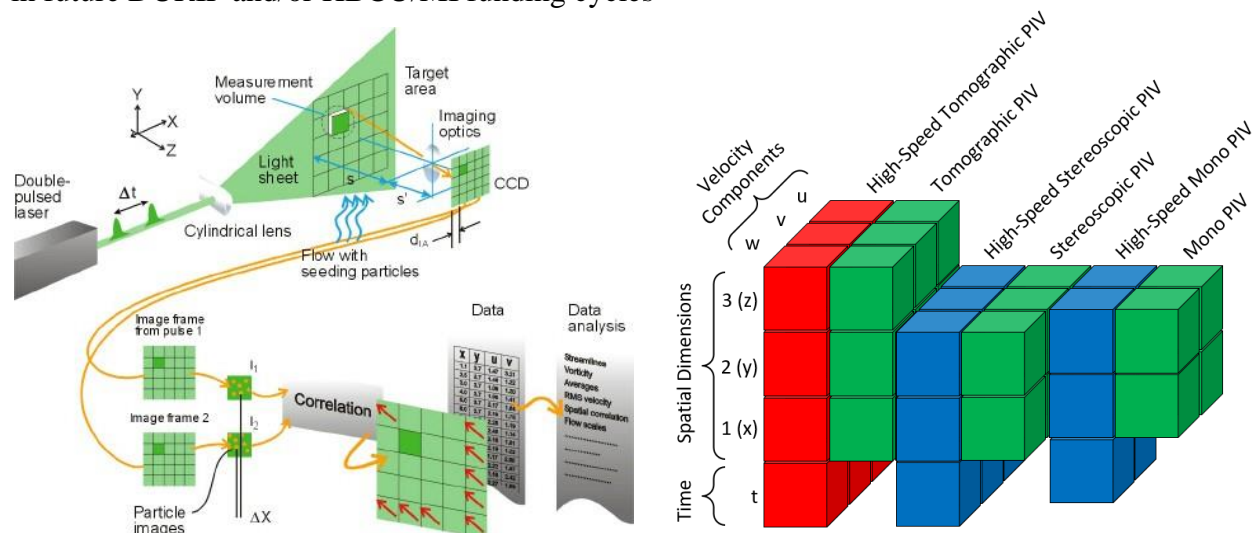
Wavelength	Repetition Frequency	Pulse Energy @ Various Burst Durations			
		1 ms	2 ms	5 ms	10 ms
1064 nm	10 kHz	1.5 J/pulse (10 pulses)	1.5 J/pulse (20 pulses)	1.2 J/pulse (50 pulses)	1.0 J/pulse (100 pulses)
	100 kHz	260 mJ/pulse (100 pulses)	200 mJ/pulse (200 pulses)	160 mJ/pulse (500 pulses)	120 mJ/pulse (1000 pulses)
	500 kHz	50 mJ/pulse (500 pulses)	40 mJ/pulse (1000 pulses)	30 mJ/pulse (2500 pulses)	25 mJ/pulse (5000 pulses)
532 nm	10 kHz	900 mJ/pulse (10 pulses)	900 mJ/pulse (20 pulses)	750 mJ/pulse (50 pulses)	600 mJ/pulse (100 pulses)
	100 kHz	150 mJ/pulse (100 pulses)	100 mJ/pulse (200 pulses)	70 mJ/pulse (500 pulses)	50 mJ/pulse (1000 pulses)
	500 kHz	20 mJ/pulse (500 pulses)	15 mJ/pulse (1000 pulses)	10 mJ/pulse (2500 pulses)	5 mJ/pulse (5000 pulses)
355 nm (22.5% of 1064 nm)	10 kHz	300 mJ/pulse (10 pulses)	300 mJ/pulse (20 pulses)	270 mJ/pulse (50 pulses)	230 mJ/pulse (100 pulses)
	100 kHz	60 mJ/pulse (100 pulses)	50 mJ/pulse (200 pulses)	40 mJ/pulse (500 pulses)	25 mJ/pulse (1000 pulses)
	500 kHz	11 mJ/pulse (500 pulses)	9 mJ/pulse (1000 pulses)	7 mJ/pulse (2500 pulses)	6 mJ/pulse (5000 pulses)
266 nm (5% of 1064 nm)	10 kHz	80 mJ/pulse (10 pulses)	80 mJ/pulse (20 pulses)	60 mJ/pulse (50 pulses)	50 mJ/pulse (100 pulses)
	100 kHz	13 mJ/pulse (100 pulses)	10 mJ/pulse (200 pulses)	8 mJ/pulse (500 pulses)	6 mJ/pulse (1000 pulses)
	500 kHz	2.5 mJ/pulse (500 pulses)	2.0 mJ/pulse (1000 pulses)	1.5 mJ/pulse (2500 pulses)	1.3 mJ/pulse (5000 pulses)

**Table 1: Operational conditions for the pulse burst laser.**

The primary motivation for acquisition of this laser is time-resolved particle image velocimetry (PIV). In its most simple form, the PIV technique produces spatially resolved 2D velocity fields on a plane. The general concept is outlined in Figure 1a. A camera is used to acquire snapshots of light (typically 532 nm from a pulsed Nd:YAG laser) scattered from particles (usually submicron) seeded in the flow. The movement of particles between successive images with a known time delay between laser pulses allows for the simple calculation of velocity. There are numerous advanced processing routines based cross-correlations that improve accuracy and spatial resolution, but the basic concept remains quite simple (velocity=distance/time). More advanced variants such as high-speed tomographic PIV provide the complete time-resolved velocity gradient tensor in a volume of the flow using four cameras or more.

The PI has been a regular user of PIV since 2004 and published the first tomographic PIV study of 3D shockwave boundary layer interaction (Threadgill and Little, 2018, 2022). PIV is known for its high spatial resolution but its utility for temporal data has been limited due to a lack of powerful high-speed lasers (10 Hz repetition rate is typical). The pulse burst laser requested here is capable of double pulse (PIV) operation at repetition rates of 100s of kHz and high energy (burst duration dependent, see Table 1). This capability, along with high-speed cameras (from DURIP) and existing hardware and software, eliminates laser repetition rate limitations, and enables highly-resolved data sets in both space and time.

Figure 1b shows the classification of PIV methods in terms of their capability for measurements in space and time. The previous capability of the TFCL is shown in green while the new capability enabled by acquisition of a pulse burst laser is shown in blue. As can be seen, the pulse burst laser provides both high-speed 2D and 3D (stereoscopic) velocity measurements on a plane. The remaining capability, high-speed tomographic PIV (red in Figure 1b), will be possible with the acquisition of two additional high-speed cameras. The PI intends to pursue this equipment in future DURIP and/or HBCU/MI funding cycles



**Figure 1: Schematic of the PIV principle (Dantec, 2020) and classification of various PIV techniques compared to laser doppler anemometry (LDA) (adapted from Scarano, 2013).**

High-speed PIV is the primary motivation for this proposal. However, pulse burst lasers offer various other possibilities for velocimetry. These include particle/aerosol tracking and filtered Rayleigh scattering (FRS) from aerosol and condensation approaches (e.g., CO<sub>2</sub>, acetone). It also enables molecular tagging/tracking in both unseeded (e.g., N<sub>2</sub>) and seeded (e.g., Krypton) flows.

These nonintrusive techniques are particularly desirable for studies where even the existence of seed particles can contaminate the experiment (e.g., quiet wind tunnels).

The utility of pulse burst lasers is not limited to velocimetry. Planar laser induced fluorescence (PLIF) is particularly compelling due to the ability to measure density and/or temperature. In fact, density measurements from a PLIF system can be paired simultaneously with velocimetry (e.g., PIV) and such techniques are growing in popularity in the field of e.g., turbulent mixing (Carter et al., 2019; Noble et al., 2019). Density measurements from a PLIF system can also be paired with mass flux measurements from constant-temperature anemometry (CTA) to calculate the velocity in flows that cannot be seeded. PLIF can also be used to measure the temperature field, which is an important and largely unaddressed variable in some experiments.

#### 4 Current Status

The pulse burst laser was delivered to AME in Fall 2022. It is currently undergoing shakedown on a static optical table but must be made mobile to serve various experimental facilities around the AME building. Thus, AME has invested state funding to acquire a custom vibration isolated optical table to enable movement of the laser around the building. The custom table has a long lead time, and we are expected to take delivery in February 2023. After this, we will be able to demonstrate the full capability of the pulse burst laser system across a variety of DoD (AFSOR, ARO, JHTO/UCAH and ONR) and DoE (NNSA) funded projects.

This equipment will also serve the advancement of education and outreach efforts beyond traditional B.S., M.S., and Ph.D. degrees through alternative programs (e.g., Master of Engineering) that target students and working professionals who require basic knowledge in specialized fields like wind tunnel testing and/or laser diagnostics applied to a specific flow regime (e.g., hypersonic). Outreach efforts will leverage ongoing successful programs in the College of Engineering, College of Education, and the University at large that target underrepresented groups in STEM. These programs engage undergraduates as well as high school students and teachers. This instrumentation will further our recruiting efforts by producing high impact visually compelling science that is critically relevant to the DoD. Collectively, these developments will make UArizona an even more effective producer of exceptional talent from all backgrounds.

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