Development and Testing of Pulse Shaping Algorithms for Optimal Laser Control

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INTRODUCTION

As **LCLS-II** moves toward a 1 MHz repetition rate, faster and more precise laser control can enable measurements across a broader experimental parameter space. To support this capability, LCLS is developing **acousto-optic modulator (AOM)-based pulse-shaping systems** for both near-infrared (NIR) and ultraviolet (UV) light.

Pulse shaping provides optical control by modifying the spectral components of an ultrafast pulse to produce a desired temporal waveform. The broader effort includes developing algorithms for **calibration, correction, and rapid scanning of pulse-shaper parameters**, with the goal of improving the accuracy, flexibility, and efficiency of laser control.

This project focuses on integrating a **Spectrum arbitrary waveform generator (AWG)** to drive the AOM. I am developing the software infrastructure needed to program the AWG, and to synchronize it with the laser and other experimental hardware.

BACKGROUND

LCLS-II 120 Hz to 1 MHz (8300x increase in repetition rate)

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Faster data acquisition & more opportunities to explore larger parameter spaces

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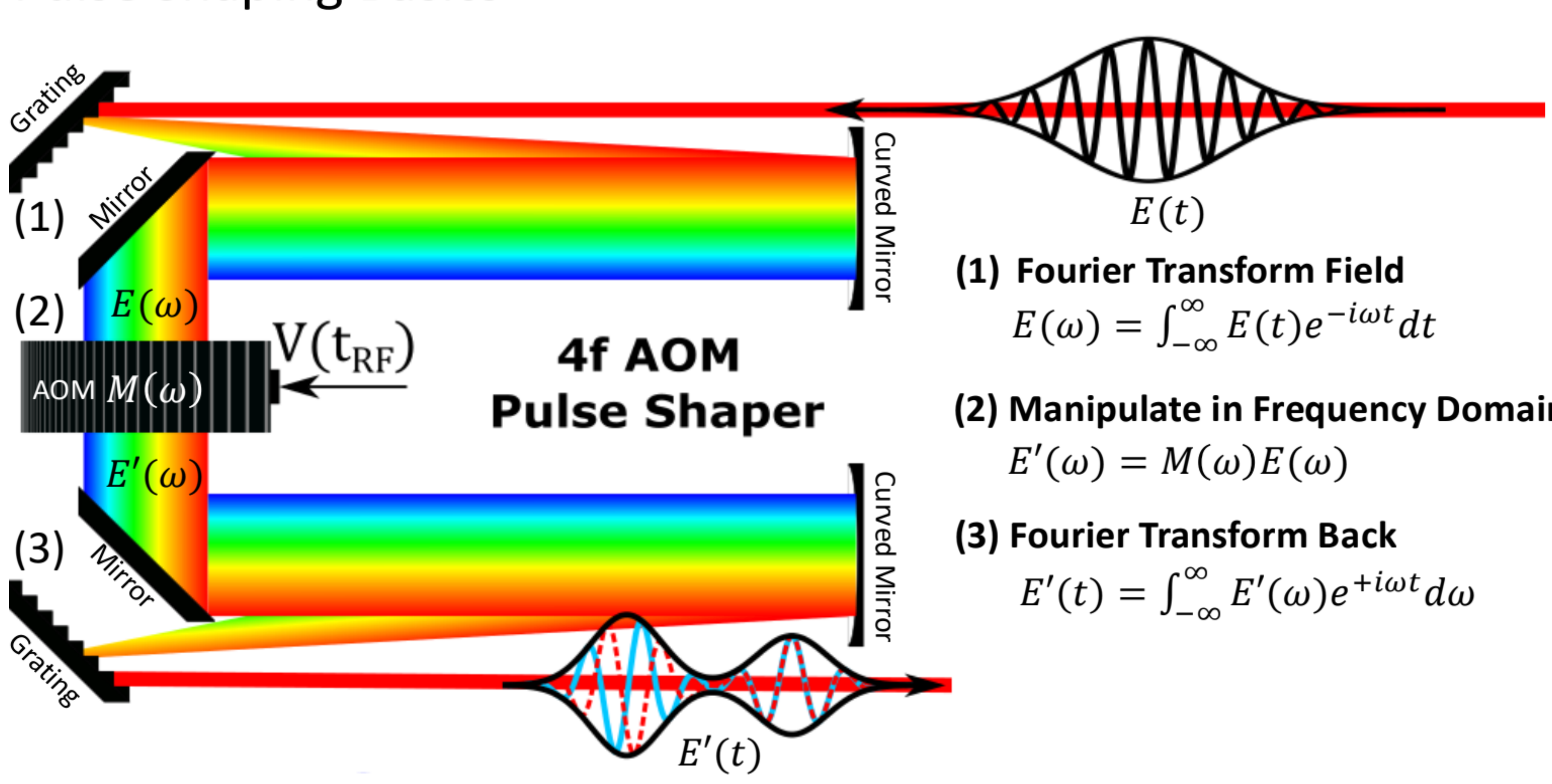
Optical Pulse shaping opens the door to new parameter spaces & improved laser flexibility

Pulse Shaping Basics



(1) Fourier Transform Field

$$E(\omega) = \int_{-\infty}^{\infty} E(t)e^{-i\omega t}dt$$

(2) Manipulate in Frequency Domain

$$E'(\omega) = M(\omega)E(\omega)$$

(3) Fourier Transform Back

$$E'(t) = \int_{-\infty}^{\infty} E'(\omega)e^{+i\omega t}d\omega$$

Map Optical Frequency to Acoustic Time

$$\omega(t_{RF}) = c_2 {t_{RF}}^2 + c_1 t_{RF} + c_0$$

Write Arbitrary RF-Acoustic Wave

$$V(t_{RF}) = A(t_{RF})\cos\left(2\pi f_{RF} t_{RF} + \phi(t_{RF})\right)$$

$$M(\omega) = A(\omega)e^{i\phi(\omega)}$$

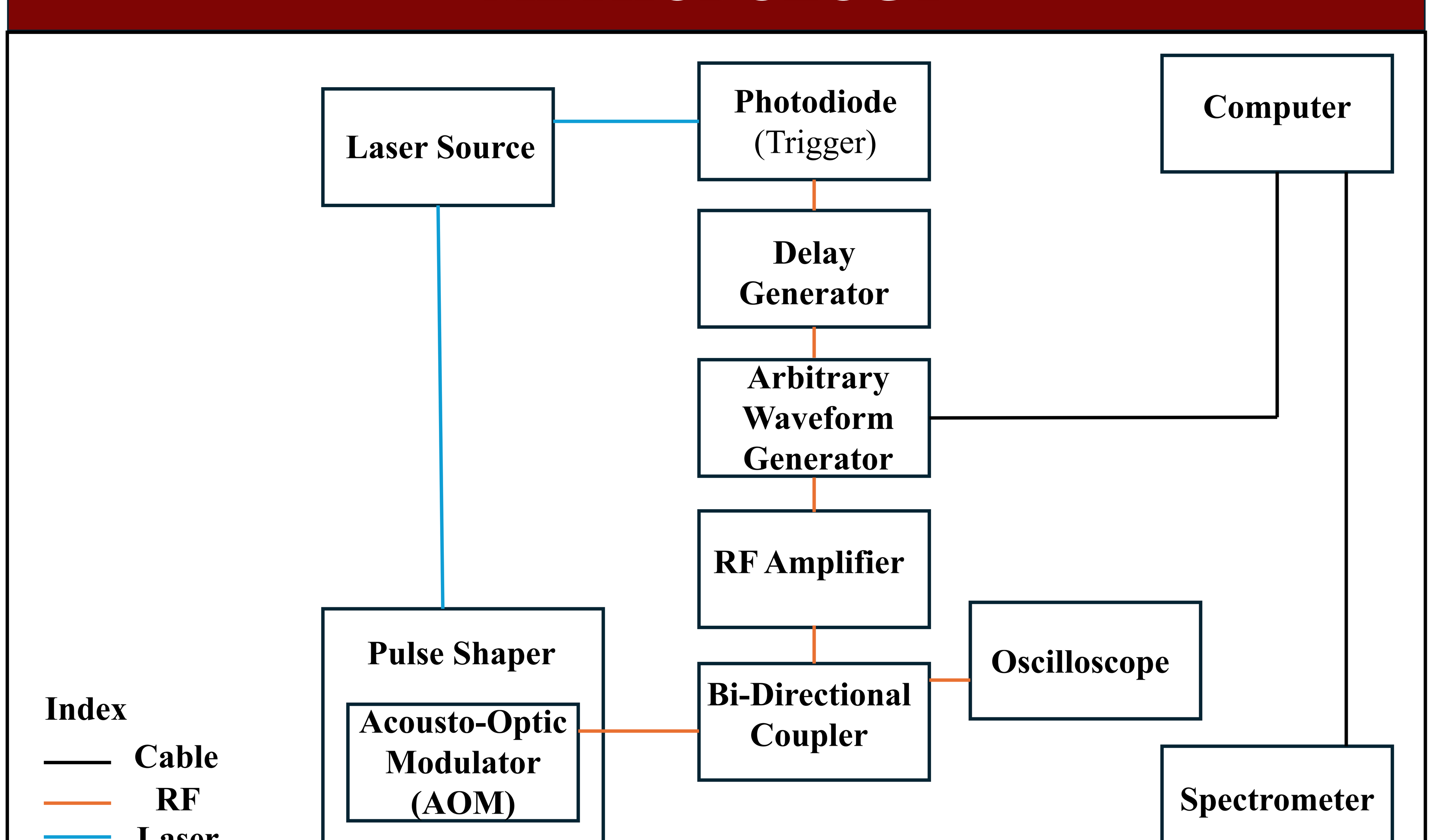
Mapping optical frequency to acoustic time enables the AOM to control individual spectral components through a highly tunable RF waveform, providing programmable control over the amplitude and phase of the ultrafast optical pulse.

PROBLEM STATEMENT

Enabling reliable, high-speed AOM pulse shaping requires:

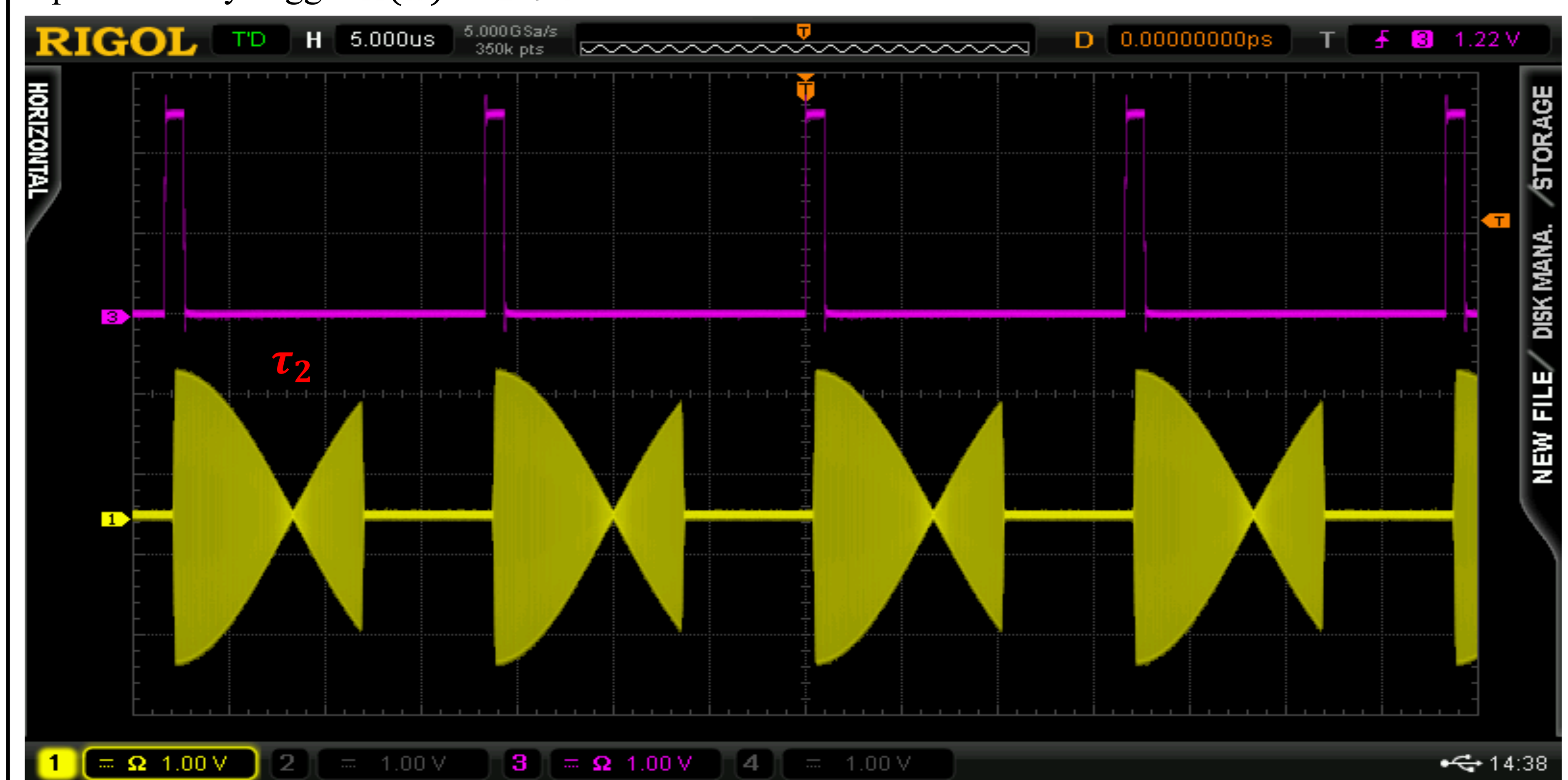
- **Robust RF waveform generation** for arbitrary pulse shaping profiles
- **Precise synchronization** between the AWG and the laser
- **Rapid waveform** updating for more efficient parameter scans

METHODOLOGY



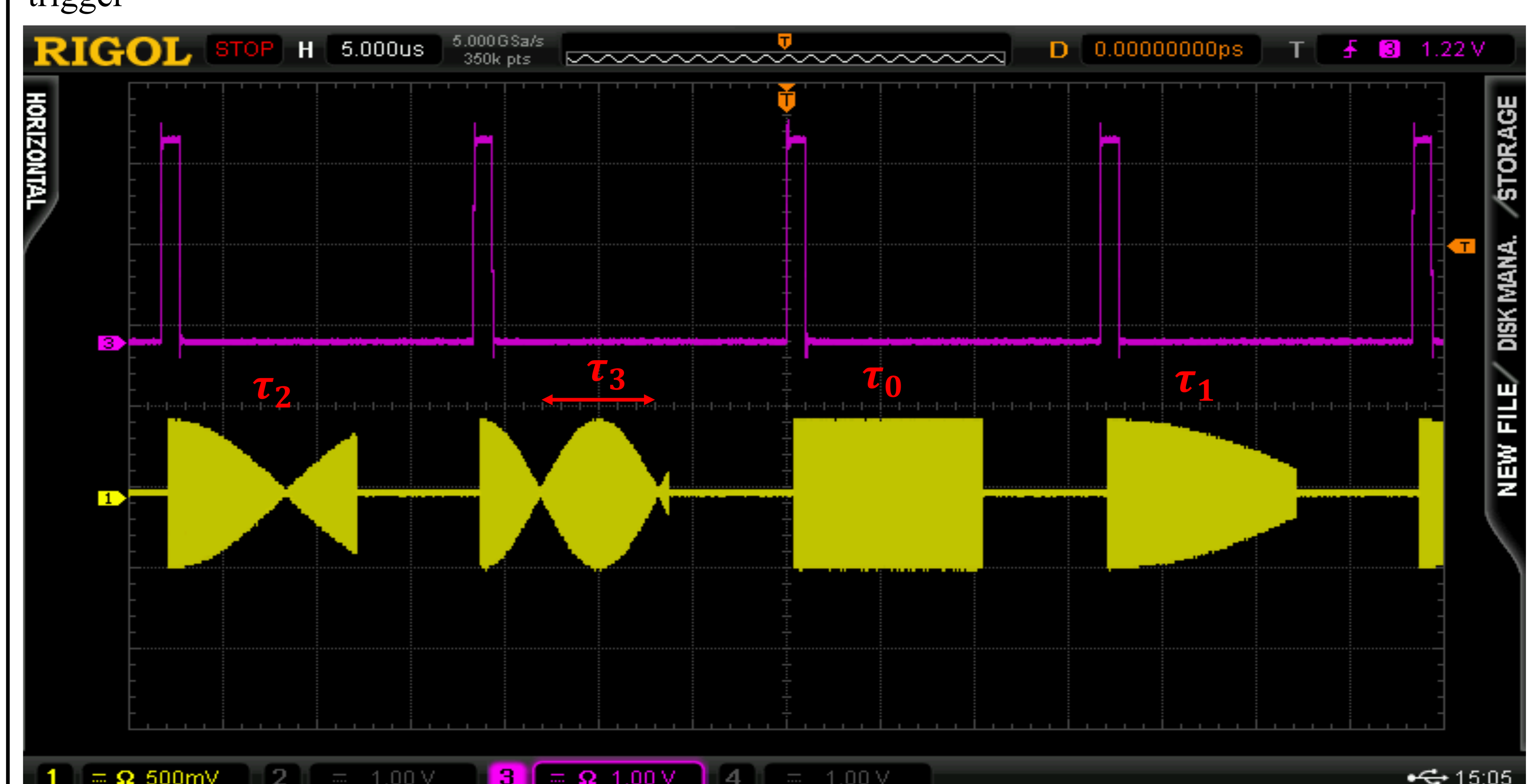
RESULTS

Fig 1: Oscilloscope trace of a complex waveform for generating optical double pulses with delay (τ_n) repeated every trigger $A(\omega) = 1 + e^{-i\omega\tau_n}$



- Scalable Waveform Control: amplitude, frequency & pulse duration
- Successful generation of arbitrary pulsed RF waveforms: double pulse optical mask
- Hardware Integration & External Triggering

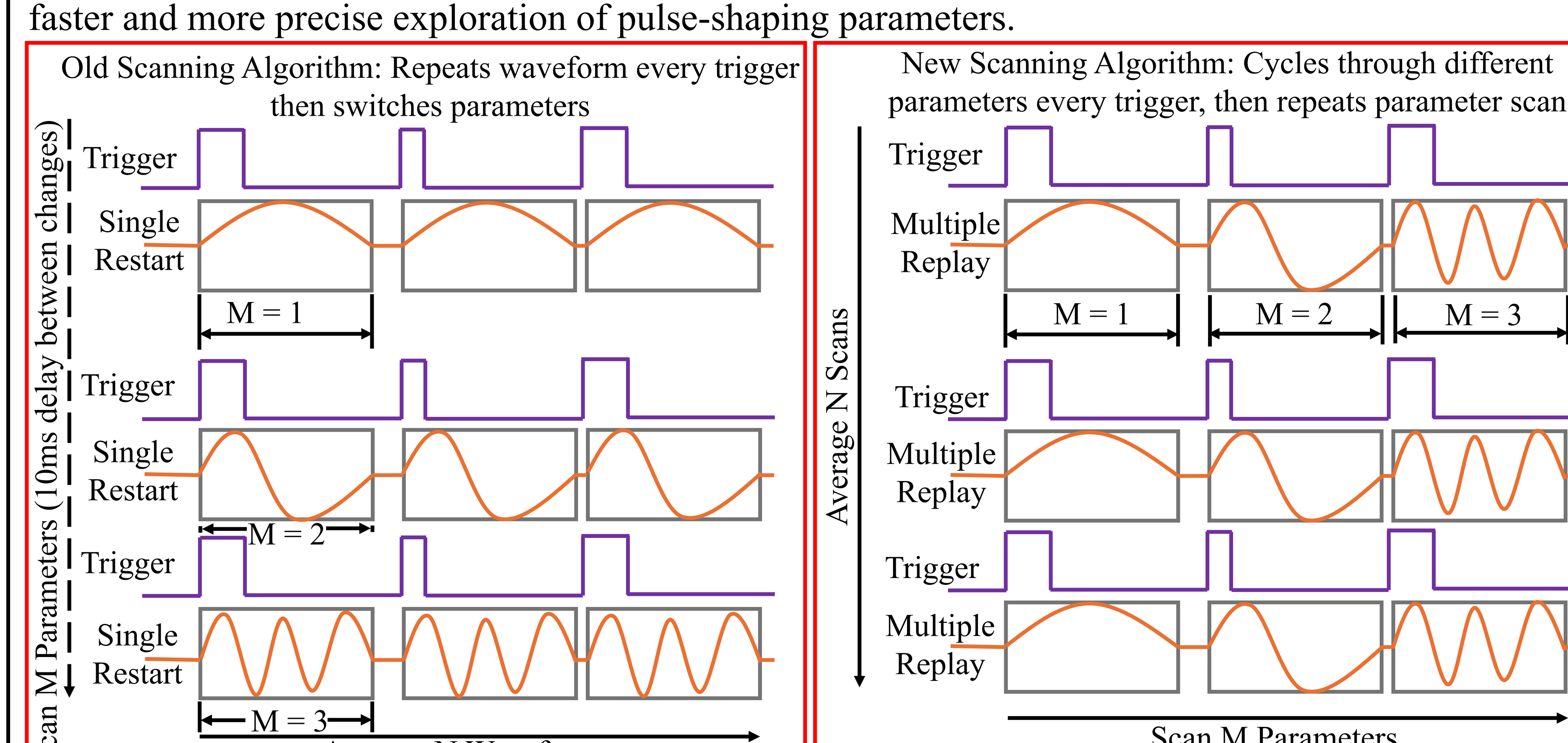
Fig 2: Complex waveform for generating optical double pulses with different delays (τ_n) every trigger



- Large waveform memory: 2 GSa at 1.25 GSa/s => 1.6s
- Programmable sequencing

FUTURE DIRECTIONS

Given the capabilities of the Spectrum AWG, we aim to upgrade the existing parameter-scanning approach from sequential, shot-by-shot control to pre-programmed waveform sequencing, enabling faster and more precise exploration of pulse-shaping parameters.



- Synchronize AWG and laser with experimental hardware
- Scan multiple RF waveforms
- Reduce communication overhead: the ~10 ms delay between parameter changes
- Characterize thermal and power drift
- Create a robust pulse shaping setup

By utilizing this new algorithm, we can move to creating a robust and rapid parameter scanning technique for optical pulse shaping at LCLS. One example being pulse characterization technique with the pulse shaper like Frequency Resolved Optical Gating (FROG)

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