Shaping Laser Pulses with RL

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August 7, 2025, RLC'25

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Ultra-short Laser Pulses

Ultrashort ($\leq 10^{-12}$ s) laser pulses are the **shortest systematic events humans can create**. They enable a range of applications, including:

① **Particle acceleration**

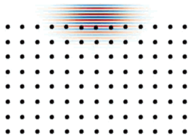


Figure: Light traversing through matter, exchanging energy thereby accelerating particles.

② **Nuclear fusion**

Scientists Achieve Nuclear Fusion Breakthrough With Blast of 192 Lasers

The advancement by Lawrence Livermore National Laboratory researchers will be built on to further develop fusion energy research.

Figure: NYT covering laser bursts used to achieve nuclear fusion ignition at the LLNL (USA), 2022.

Maximize Intensity by Minimizing Duration

Laser bursts convey energy in both time and space.

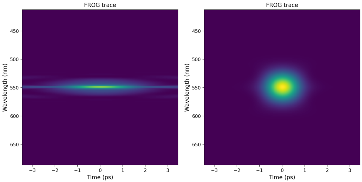


Figure: (left) Poorly temporally-focused pulse (right) Temporally-focused pulse

Particle acceleration & fusion ignition both require high-intensity bursts.

$$PI_t \propto \frac{2E}{\int I_\psi(t)dt}$$

Intensity grows when:

- Increases in the pulse energy, $E \uparrow$
- Decreases in pulse duration $\boxed{\int I_\psi(t)dt \downarrow}$

Minimizing Duration = Optimal Shaping

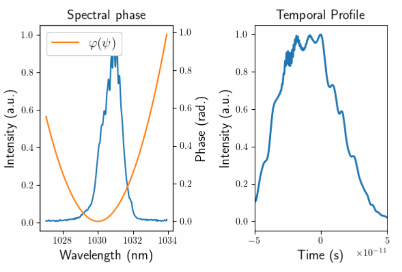
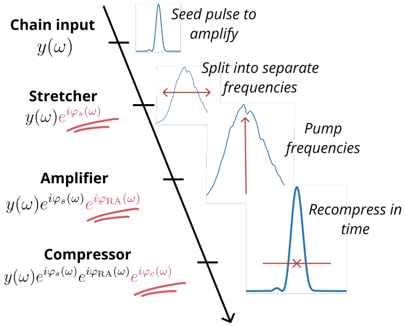


Figure: (left) Spectral pulse, phase in yellow (right) Resulting temporal profile.

Controlling the phase **in the frequency domain** impacts the pulse's duration **in the temporal domain**. Shaping consists of:

- ① Stretching the pulse into fundamental frequencies
- ② Amplifying the different frequencies (**non-linear**)
- ③ Recompressing in time, aligning frequencies yielding constructive interferences

Minimizing Duration = Optimal Shaping



Controlling the phase **in the frequency domain** impacts the pulse's duration **in the temporal domain**.

- 1 Stretching the pulse into fundamental frequencies Can control
- 2 Amplifying the different frequencies (**non-linear**) Can't control
- 3 Recompressing in time, aligning frequencies yielding constructive interferences Can't control

Shaping feels like "Anon, *ngmi*"

① State reconstruction

- Lasting pico/attoseconds, ultra-short temporal profiles **cannot be directly measured**.
- Measuring the intensity achieved is a **destructive process**.

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- Shaping system's **parameters change day by day**, and not always for fully modelled reasons.
- The processes of non-linear amplification and phase accumulation themselves are not fully understood

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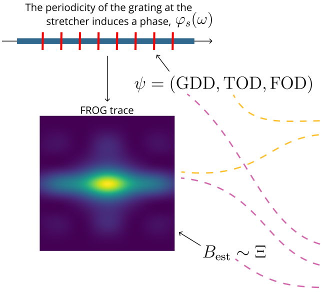
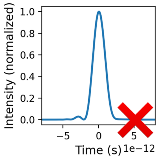
③ **Fragile in real-world settings**

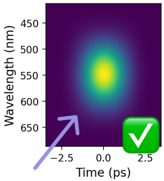
- Real-world shapers are delicate machines needing proper care relatively to the control applied
- Besides being correct, **controls need to be appropriate**, both in absolute and relative terms.

① Use unstructured observations

Bypass noisy pulse reconstructions, use raw diagnostics **(images)** only.
Diagnostic measurements are **not destructive**.

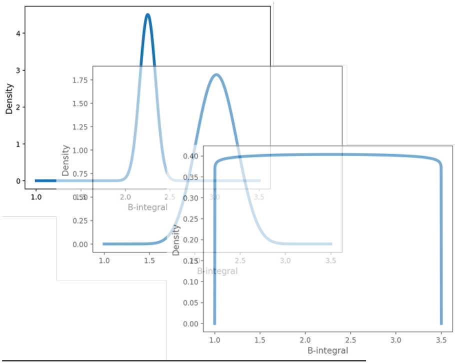


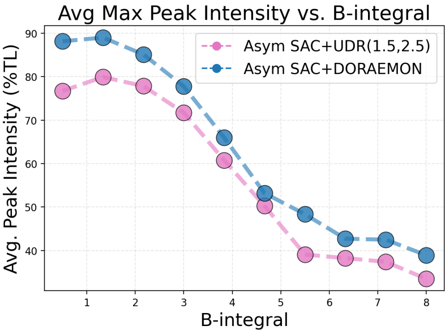




② Induce robustness to dynamics

Automatically adapt the randomization distribution based on performance during training [1]

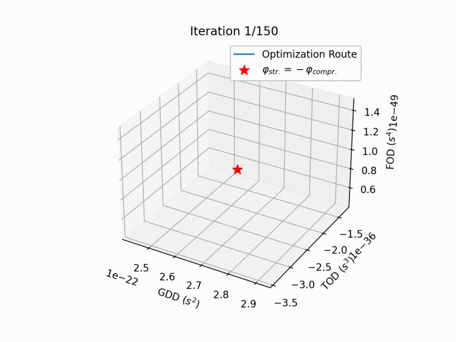


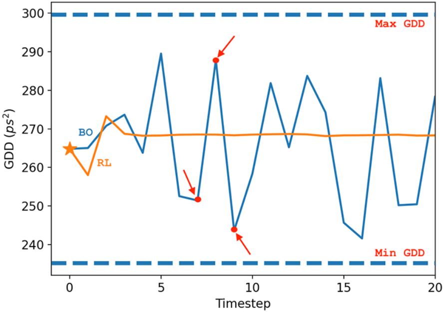


[1] "Domain randomization via entropy maximization", Tiboni et al., ICLR 2024

③ Train in a (coarse) simulator

Avoid exploration on real-world systems by **training in simulation**, allocating erratic behavior to in-simulation training





Deep RL for pulse shaping

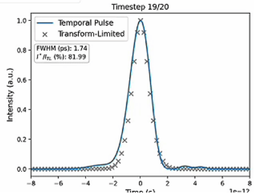
① Asymmetric Soft Actor-Critic

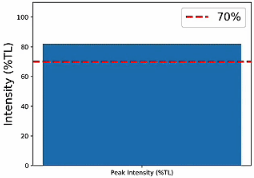
Augment observations fed to the critic network with the dynamics parameters, $B_{\text{est.}}$.

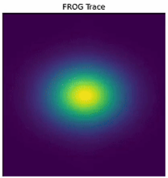
② Entropy-driven Domain Randomization

Avoid manually tuning $\Xi : B_{\text{est.}} \sim \Xi$, adapting it based on training signal.

We train a controller to **safely tune** laser parameters for intensity maximization **across dynamics** and using **image observations only**.







Conclusions

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Environment code `gym-laser` & testbed are both online and **open-source**!

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