Shaping Laser Pulses with RL

Francesco **Capuano**[(1,2)], Davorin **Peceli**[(3)], Gabriele **Tiboni**[(4,5)]

[1] ENS Paris-Saclay [2] Hugging Face [3] ELI Beamlines

[4] JMU Würzburg [5] TU Darmstadt

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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

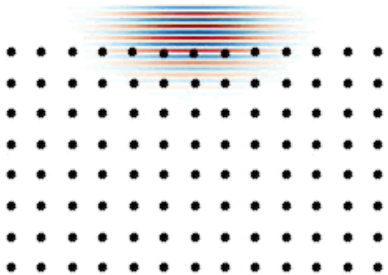


Figure: Light traversing through matter, exchanging energy thereby accelerating particles.

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.

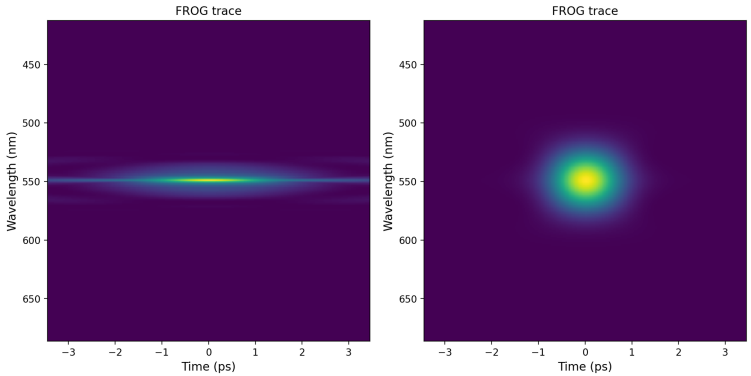


Figure: (left) Poorly temporally-focused pulse (right) Temporally-focused pulse

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

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

Intensity grows when:

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

Optimal Shaping = Minimizing Duration

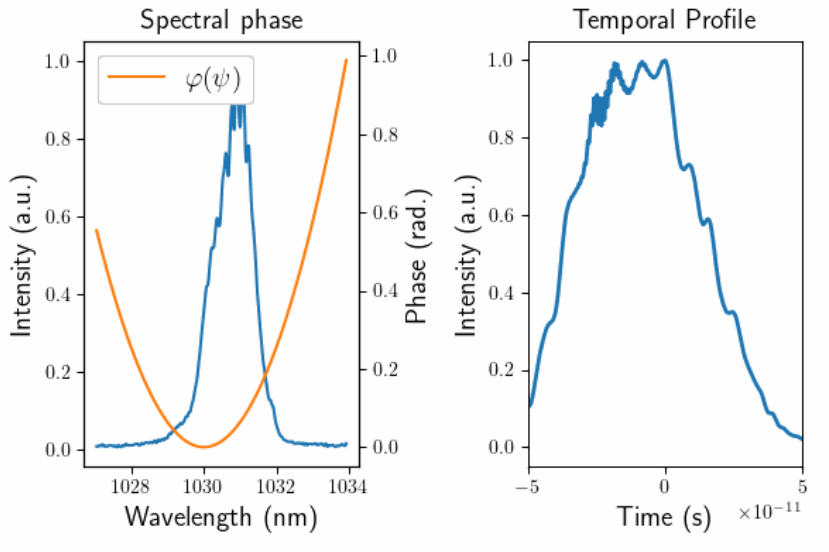
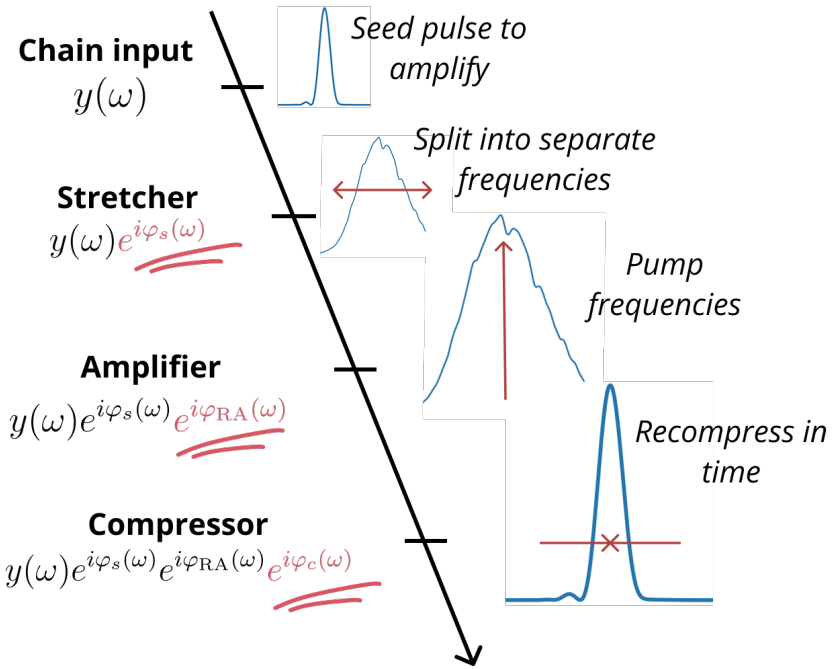


Figure: (left) Spectral pulse, phase in yellow (right) Resulting temporal profile.

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

Optimal Shaping = Minimizing Duration



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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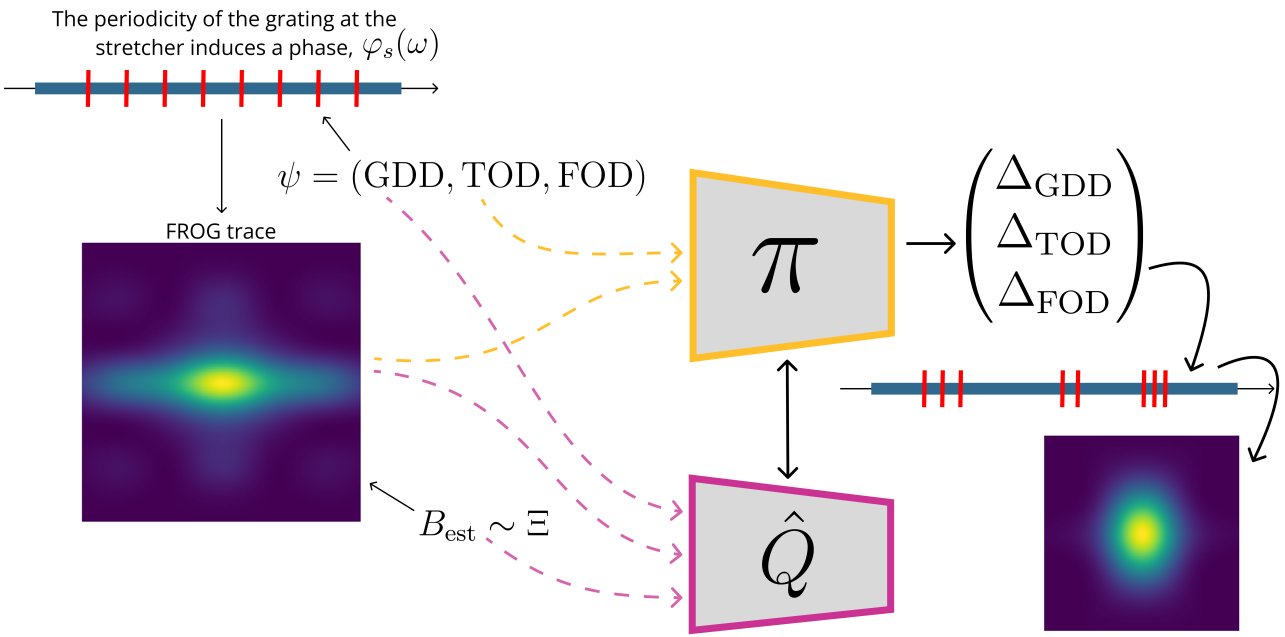
③ Fragile in real-world settings

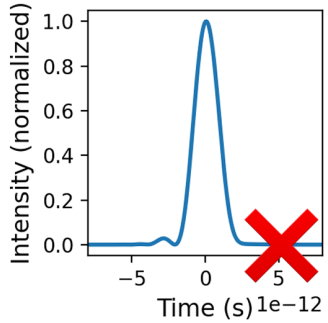
- Real-world shapers are delicate machines needing proper care relatively to the control applied
- Besides being correct, **controls need to be appropriate**, both in absolute and relative terms.

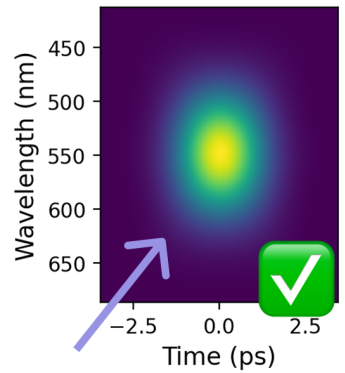
Deep RL To The Rescue (1/3)

① Use unstructured observations

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



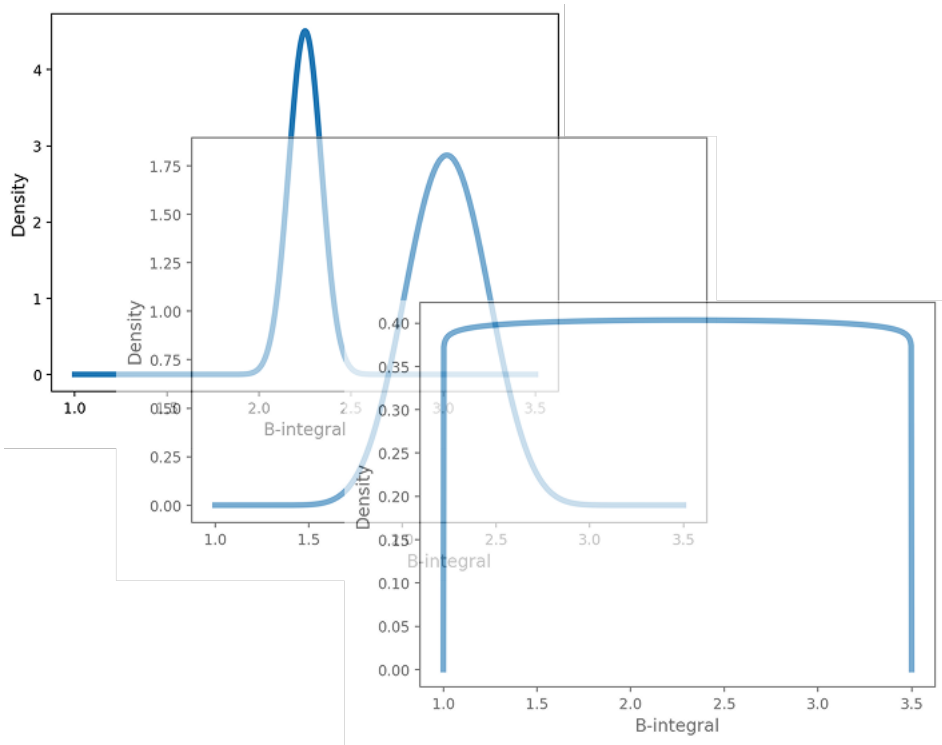


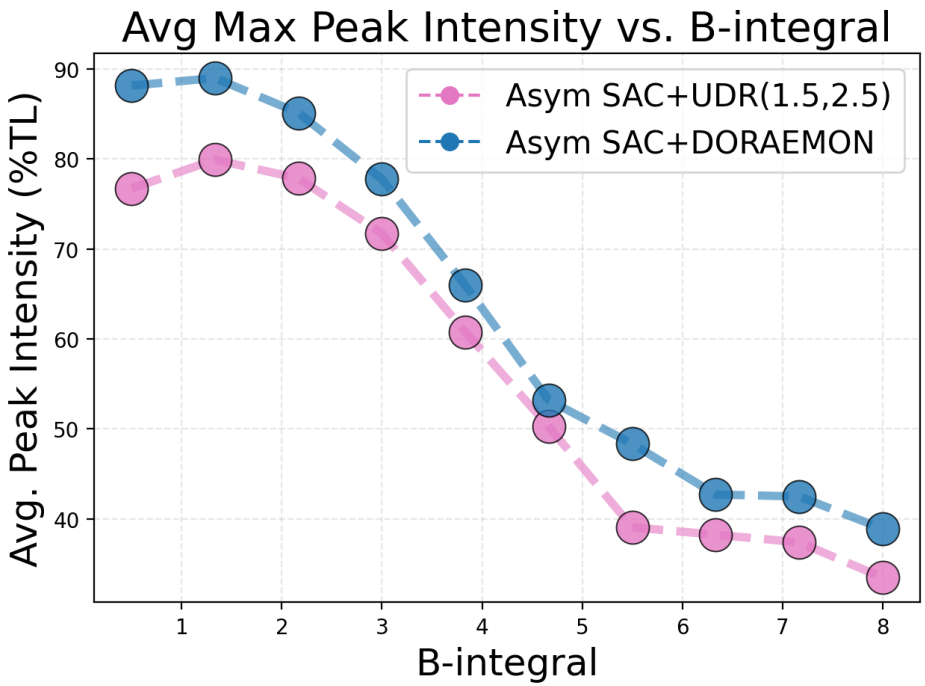


Deep RL To The Rescue (2/3)

② Induce robustness to dynamics

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



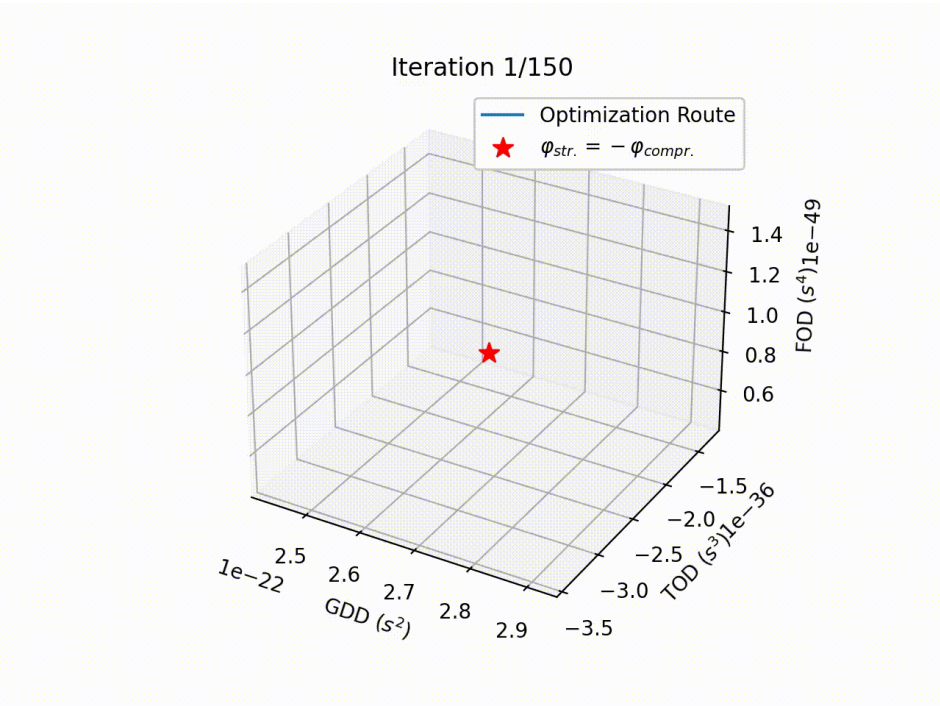


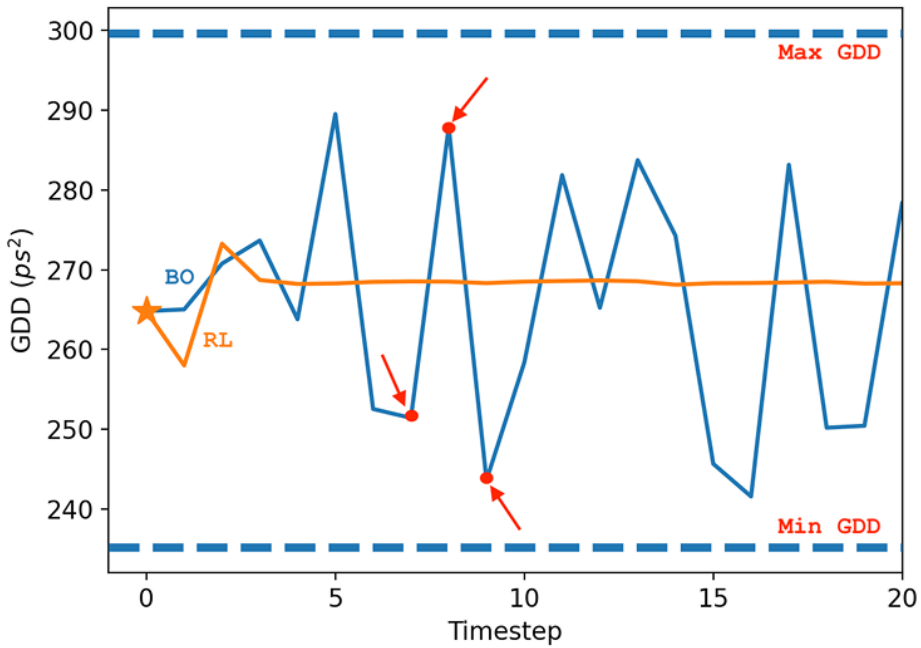
[1] "Domain randomization via entropy maximization", Tiboni et al., ICLR 2024

Deep RL To The Rescue (3/3)

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

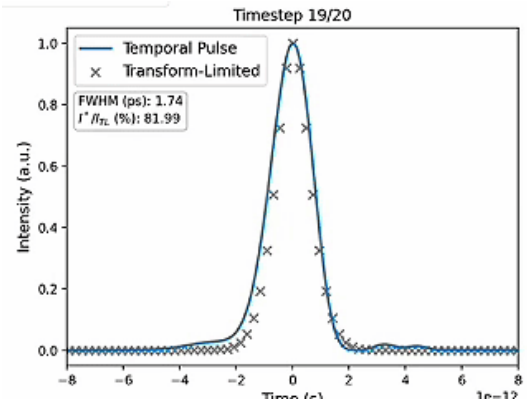
① Asymmetric Soft Actor-Critic

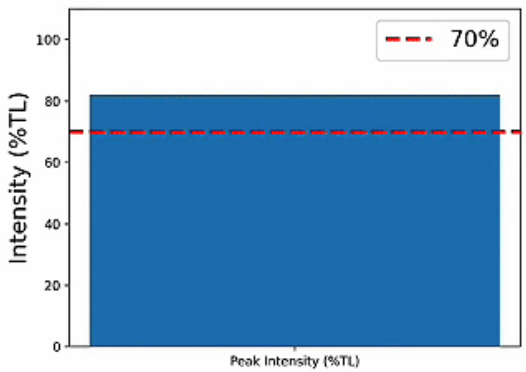
Augment observations fed to the critic network with the dynamics parameters, $B_{\text{est.}}$.

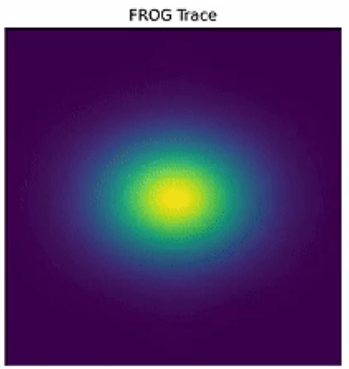
② Entropy-driven Domain Randomization

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**.







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

Questions? Poster 21