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Machine Learning Approach to Temporal Pulse Shaping for the Photoinjector Laser at CLARA

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Abstract

The temporal profile of the electron bunch is of critical importance in accelerator areas such as free-electron lasers and novel acceleration. In FELs, it strongly influences factors including efficiency and the profile of the photon pulse generated for user experiments, while in novel acceleration techniques it contributes to enhanced transformer ratio for drive/witness beam interactions. Work is in progress at the CLARA facility at Daresbury Laboratory on temporal shaping of the ultraviolet photoinjector laser, using a fused-silica acousto-optic modulator. Generating a user-defined (programmable) time-domain target profile requires finding the corresponding spectral phase configuration of the shaper; this is a non-trivial problem for complex pulse shapes. Physically informed machine learning models have shown great promise in learning complex relationships in physical systems, and so we apply machine learning techniques here to learn the relationships between the spectral phase and the target temporal intensity profiles. Our machine learning model extends the range of available photoinjector laser pulse shapes by allowing users to achieve physically realisable configurations for arbitrary temporal pulse shapes.

Introduction

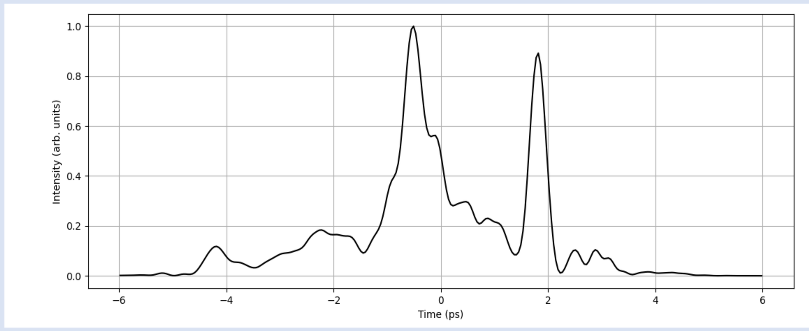
- The temporal profile of the electron bunch is of critical importance in accelerator areas such as free-electron lasers and novel acceleration.
- At CLARA, we have built an apparatus for shaping photoinjector laser pulses, using a 4f shaping scheme with an acousto-optic modulator (AOM) as the spatial light modulator.
- Generating a user-defined (programmable) time-domain target profile requires finding the corresponding spectral phase configuration of the shaper; this is a non-trivial problem for complex pulse shapes.

Methodology

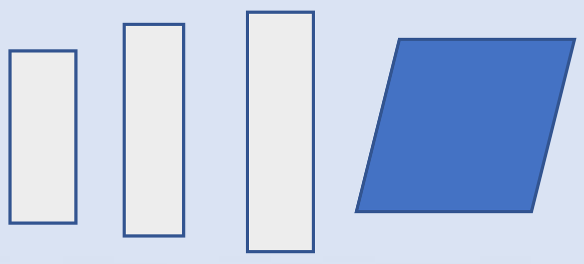
- To solve this problem, we have developed a physically informed neural network (PINN) which predicts the required spectral phase configuration to produce a target pulse shape, taking into account physical constraints of the apparatus to ensure the predicted configuration is realisable.
- We train the network with physical constraints and a loss function chosen to provide temporal translation invariance.
- This approach both reduces the data requirements of our model and constrains the search space within a physically realisable range. Thus, we can be confident that predictions of temporal intensity profiles produced by our model will be achievable experimentally, in contrast to existing methods which require iteration to refine.

Arbitrary Target Temporal Profile

A user specifies an arbitrary temporal pulse profile.



Physically Informed Machine Learning Model

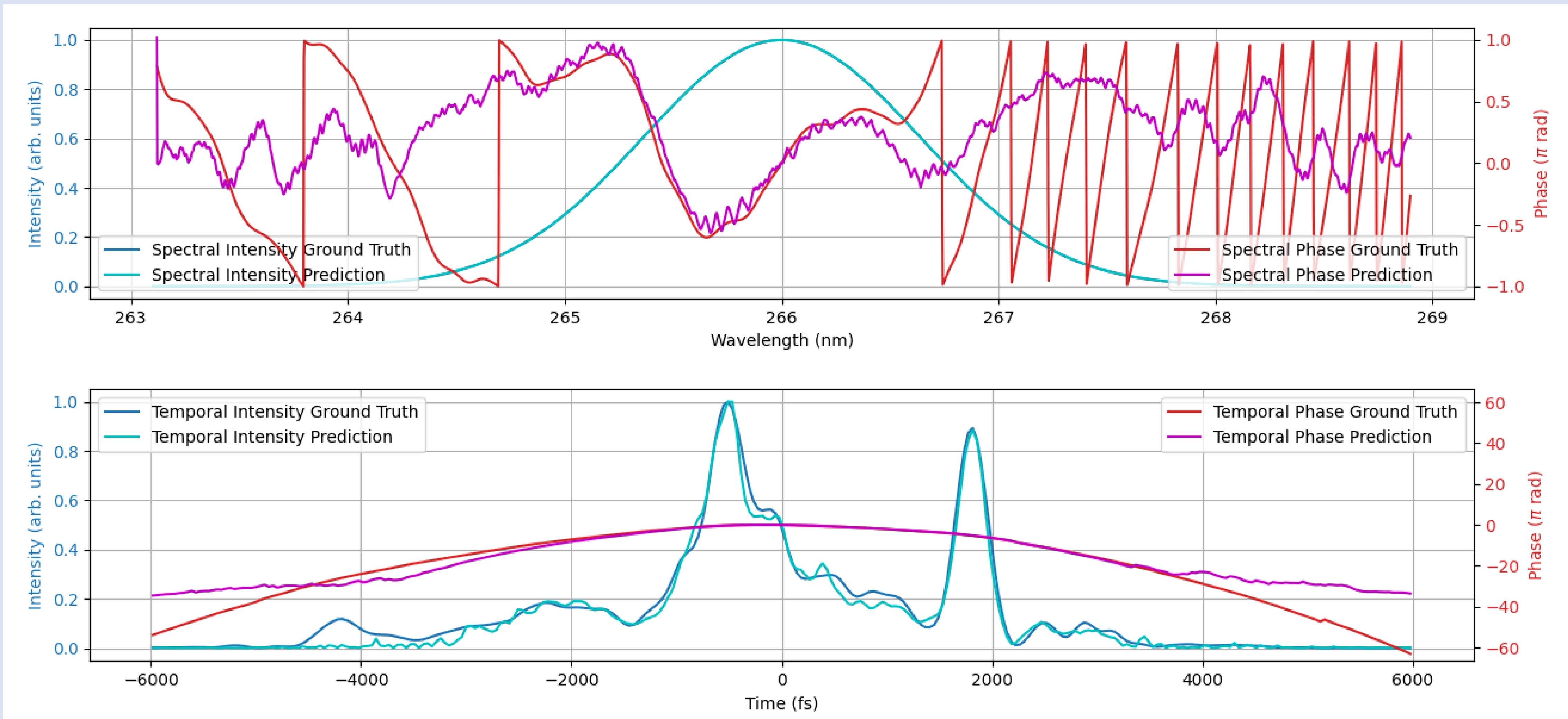


$$\frac{1}{N}\sum|\Delta_+(e^{i\varphi(\omega)})| * \eta\sigma(|\Delta_+(e^{i\varphi(\omega)})| - 0.15\dot{3}); \eta = 100$$

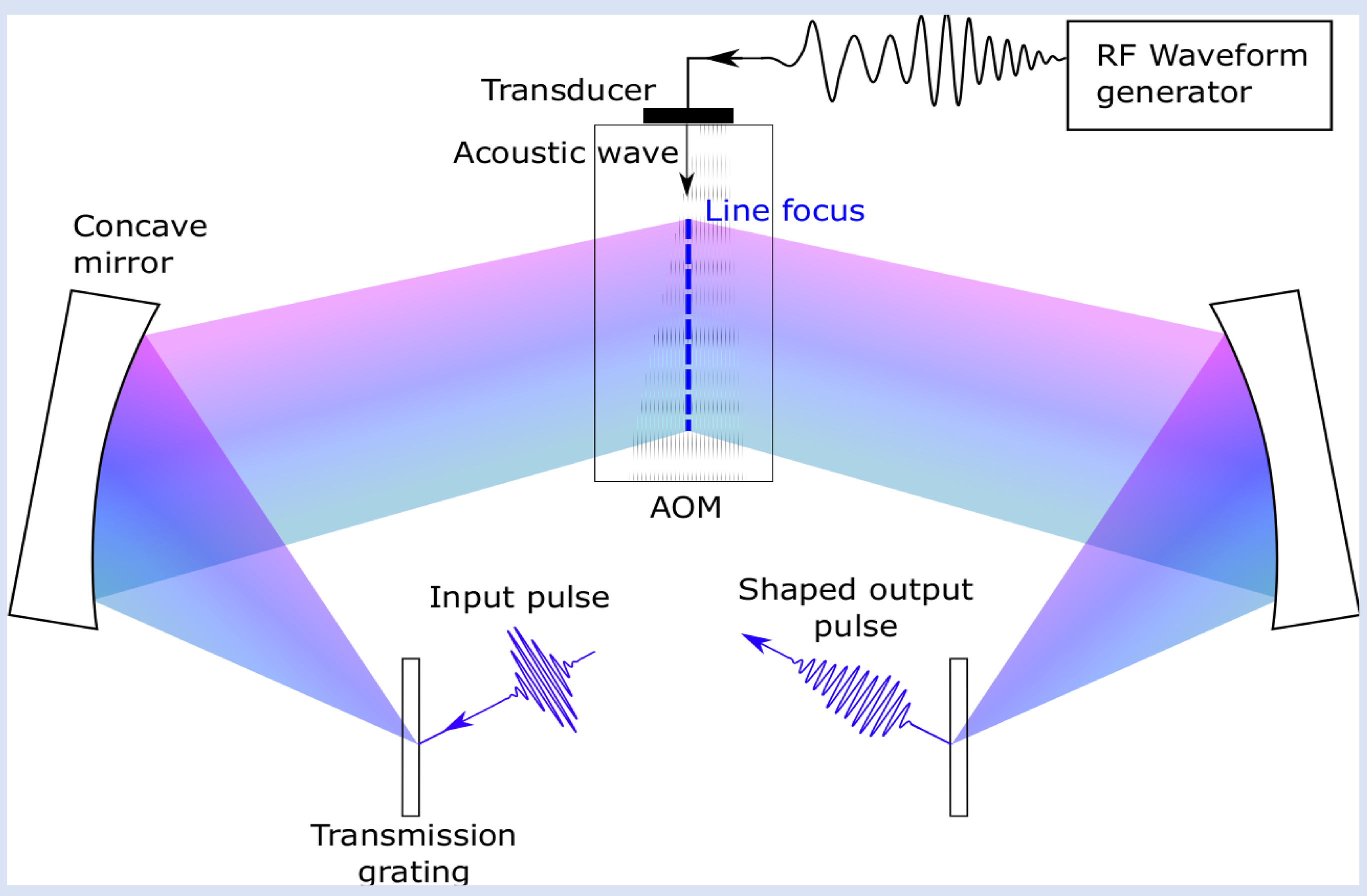
Using the known physical limits of the acousto-optic modulator, the physically informed neural network predicts a spectral phase mask which will produce the profile *and* be physically realisable on the AOM.

We limit the phase change per frequency step using the regulariser shown and the Pearson correlation coefficient to allow for temporal translation in the output space

Predicted Spectral Phase Profile



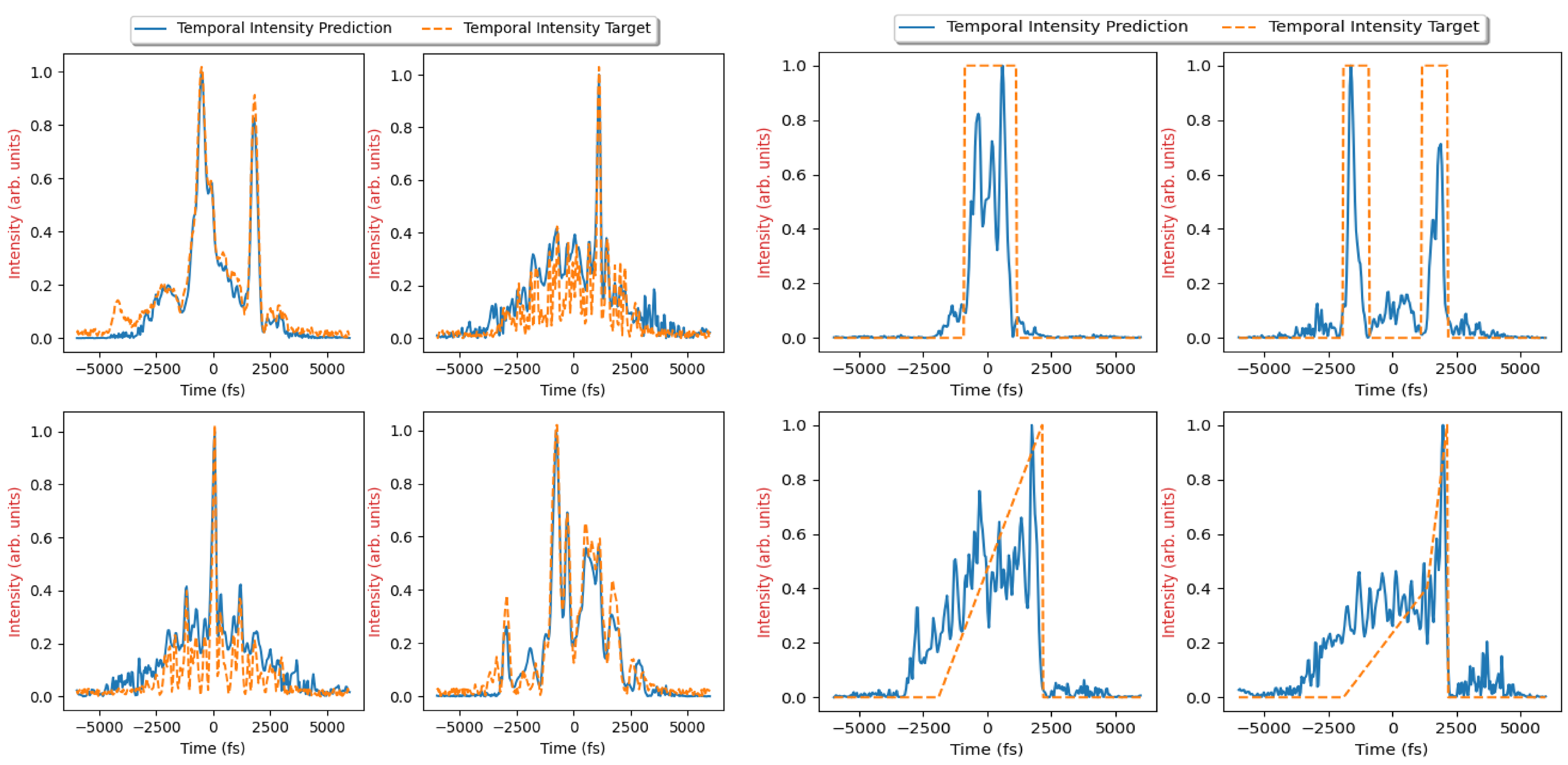
Temporal Shaper



The resulting spectral phase mask will be passed to the AOM, and the target pulse shape will be produced.
Changing laser spectral phase by modulating acoustic wave phase broadens the acoustic spectrum.
Spectral phase mask is physically limited by acoustic bandwidth of AOM.

Results

- While other techniques can generate spectral phase masks which produce strong matches for the target temporal profile, they do so using physically impossible spectral phase transitions.
- Our model constrains itself within physically realisable limits, and so spectral phase predictions can be applied to hardware directly without further modification.
- We produce high quality matches that are physically achievable, as shown below.



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