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REAL-TIME PROGRAMMABLE SHAPING FOR ELECTRON AND X-RAY SOURCES

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Abstract

The next generation of augmented brightness X-ray free electron lasers (XFELs), such as the Linac Coherent Light Source-II (LCLS-II), promises to address current challenges associated with systems with low X-ray cross-sections. Typical photoinjector lasers produce coherent ultraviolet (UV) pulses via nonlinear conversion of an infrared (IR) laser. Fast and active beam manipulation is required to capitalize on this new generation of XFELs, and controlling the phase space of the electron beam is achieved by shaping the UV source and/or via IR shapers [1, 2]. However current techniques for such shaping in the UV rely on stacking pulses in time, which leads to unavoidable intensity modulations and hence space-charge driven microbunching instabilities [3]. Traditional methods for upconversion do not preserve phase shape and thus require more complicated means of arriving at the desired pulse shapes after nonlinear upconversion [4]. Upconversion through four-waving mixing (FWM) allows direct phase transfer, convenient wavelength tunability by easily changeable phase matching parameters, and also has the added advantage of greater average power handling than traditional $\chi(2)$ nonlinear processes [5, 6]. Therefore, we examine a possible solution for e-beam shaping using a machine learning (ML) implementation of real-time photoinjector laser manipulation which shapes the IR laser source and then uses FWM for the nonlinear upconversion and shaping simultaneously. Our presentation will focus on the software model of the photoinjector laser, the associated ML models, and the optical setup. We anticipate this approach to not only enable active experimental control of X-ray pulse characteristics but could also increase the operational capacity of future e-beam sources, accelerator facilities, and XFELs [7].

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INTRODUCTION AND MOTIVATION

Ground-up design of high power chirped pulse amplification (CPA) systems is not trivial. Choosing the correct hardware and determining limitations for a particular laser system– such as damage thresholds for optics [8] and amplifiers as well as bandwidth limitations for shaping– can be a challenging task, especially for systems involving custom design amplifiers, pre-CPA programmable pulse shapers, or a series of up-/down-conversion stages. Start-to-end (S2E) software models can greatly inform laser system design decisions and aid in understanding limitations or trade-offs in performance parameters. To an even greater extent, as we enter new stages of ML-driven photonics and optical system design [9], the need for S2E-based data generation to inform these ML models and reduce parameter searches in the lab will become increasingly desired. Furthermore, the potential symbiosis between experiment and software model means experiment can improve the S2E models, which in turn can drive improvements in the system design. This relationship with experiment-corrected software model design could even open the possibility for using these models for material design via inverse engineering.

At LCLS-II, we are developing real-time adaptable photoinjector shaping techniques to increase the electron beam brightness and enhance future modes of X-ray lasing operation, some of which may require advanced models, such as machine learning, to determine optimal spatio-temporal distribution of the photoinjector laser pulses. Thus, we have developed and used this S2E model to both determine the limitations of our pulse shaping techniques and to generate data for training the ML models.

MODEL AND RESULTS

The LCLS-II photoinjector laser system starts with an IR mode-locked oscillator shaped in spectral phase and amplitude by an acousto-optic programmable dispersive filter,

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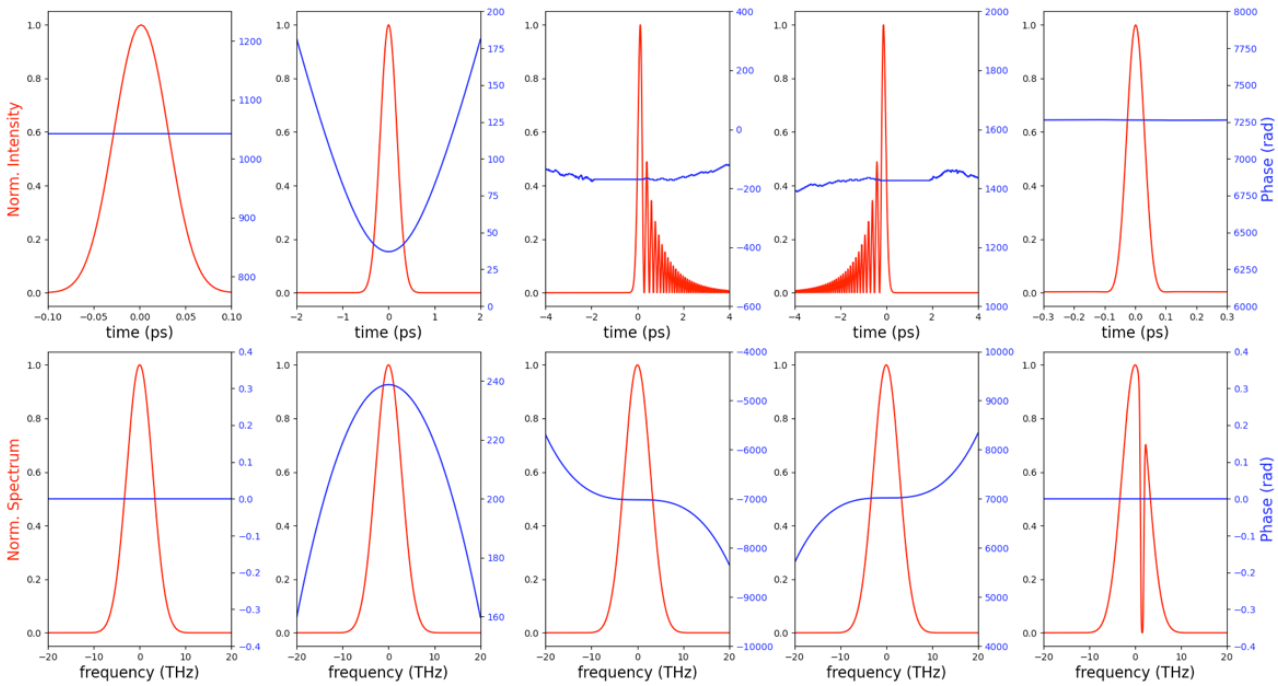

Figure 1: Shows the time domain (top row) intensity (red) and phase (blue) profiles and frequency domain (bottom row) spectrum (red) and spectral phase (blue) for various types of pulse shaping: no shaping (first column), added second-order dispersion (second column), positive third-order dispersion (third column), negative third-order dispersion (fourth column), and spectrum shaping (fifth column).

then amplified by an Yb:KGW regenerative amplifier. The amplified IR beam is finally subject to an ensemble of non-linear upconversion stages including sum frequency generation (SFG) [4], cascaded second harmonic (SH) stages, or FWM to generate UV.

The initial IR pulse in our S2E model is a spectrum collected from our oscillator. We then directly shape the output of our oscillator using a Dazzler [10]. The Dazzler is a programmable acousto-optic device that uses an RF signal to impart a diffraction pattern within a crystal in order to modify the input signal. The S2E model uses seven parameters to perform amplitude and phase modulation where amplitude shaping uses a frequency domain super Gaussian transfer function and phase shaping uses a frequency domain Taylor expansion.

The regenerative amplifier (RA) follows the pulse shaper and amplifies the signal before upconversion. The main tuning parameters for this portion of the model include crystal length, ion density, material emission and absorption cross section spectra, pump power as well as other RA parameters. This simulation uses modified Frantz-Nodvik equations [11] in the wavelength domain to capture the change in spectral shape, the shift in central wavelength, and the build-up in energy. The simulation centers around the emission and absorption peaks for Yb:KGW for the pump and seed processes and does not require phase information.

Lastly, the output of the RA feeds into the upconversion stage. We are currently exploring upconversion through FWM in gas-filled hollow-core fibers. Our aim is to use a pulse shaper in the near infrared to directly control the emission bandwidth, wavelength and phase of the emitted deep-ultraviolet light pulse. Such new generation of light sources would provide light guidance in a hollow-channel over an unmatched spectral band, dynamic control of the linear and nonlinear optical properties by filling the hollow-core with different gases at different pressure or temperatures, and high-average power handling and peak-power delivery, up to kW and GW respectively [5, 6].

The current simulations of the FWM process are based on solving the coupled-mode equations of the complex amplitudes of the three interacting waves with respect to their propagation inside the fiber [12]. The calculations are made in the frequency domain considering a frequency dependent dispersion and nonlinearity of the gas used inside the fiber without resorting to the undepleted pump approximation. This allows for the study of output redistributions of the power among the interacting waves. An optimization is run across various parameters such as gas-type, pressure, inner-core radius, and length of the fiber for different interacting wavelengths to minimize the group-velocity dispersion (GVD) and maximize the conversion efficiency. The simulations show a high conversion efficiency for fiber of 1 m length and 100 µm inner radius filled with Krypton gas at 0.8 bar pressure. The total phase of the nonlinear interaction as a function of the propagation along the fiber length is again realized by solving the coupled-mode equations of the complex amplitudes of the three interacting waves

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[12]. To study the spectral phase transfer from the input signal beam (at 1025 nm) to the generated idler beam (at 341 nm) through the FWM process, we assume that the spectral phase of the pump beam remains constant through the FWM process [6]. Then the spectral phase of the FWM signal is realized by plotting a few initial order terms of the Taylor expansion of the spectral phase of the amplifier beam.

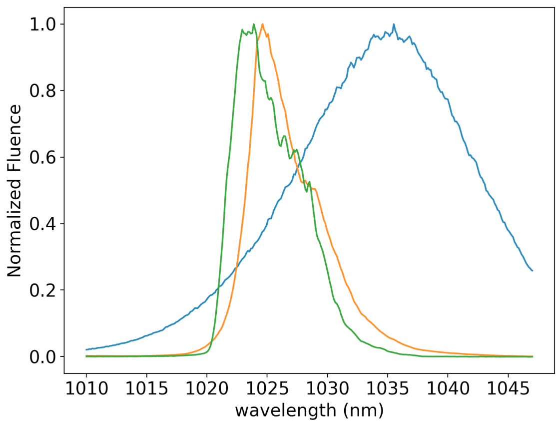
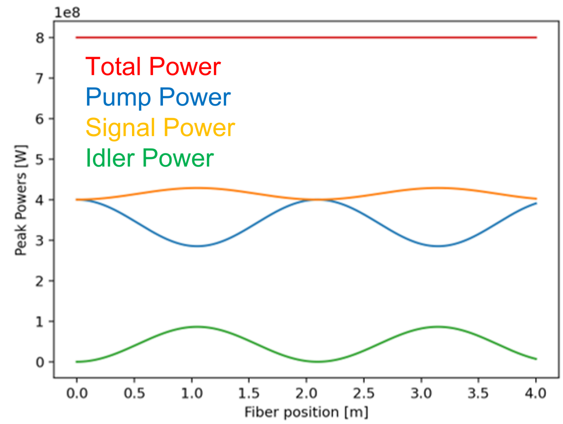


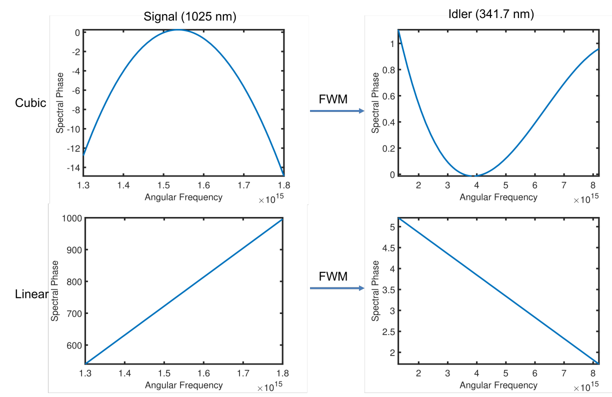
Figure 2: Functioning amplifier model with direct oscillator input (blue) to amplifier with true (green) and simulated (orange) outputs from amplifier.

In our presentation, we will demonstrate the S2E model by showing several portions of the model – IR pulse shaping, amplifier, and FWM. Figure 1 shows the first portion of the S2E model, the pulse shaper. Here, we demonstrate some of the fundamental pulse shaping capabilities. We start by showing the oscillator output, not shaped. Then show added second-order dispersion, positive third-order dispersion, negative third-order dispersion, and spectrum hole carving. These examples are important for several reasons. First, they have specific potential application for the desired pulses for our photoinjector. For example, the second-order dispersion widens the time-domain pulse, so we can bring our pulse shapes closer to the required 25 ps pulse widths. Then for the third-order dispersion, we are able to chirp the pulse. This could be useful for driving instabilities that generate mircobunching in the electron bunch in the XFEL, which is used for generating attosecond X-ray pulses. Apart from specific application to photoinjector shaping, these examples of shaping are what is used for training the ML models where we scan parameter combinations using these types of shaping. Our ML studies will show what the shaping parameters should be based on the method of upconversion used.

In figure 2, the RA operation is shown next. For this, the direct output of the oscillator (blue) is fed into the amplifier model. The simulated output (orange) and the true output (green) are shown. We can see the simulated and true closely match each other, exhibiting similar gain narrowing and output peaks. To yield this result, we used an error reduction analysis by tuning amplifier crystal orientation, ion density, and crystal length among other parameters and comparing the simulated output with the true output of the spectrum collected in lab.



(a)



(b)

Figure 3: (a) Energy transfer between the three waves as they propagate within the fiber; (b) Spectral phase transfer signal to idler through FWM process

Figure 3a shows the power distribution among the three interacting waves along the length of the fiber for the FWM process. The input signal IR beam is at 1025 nm and the pump, generated from the SHG of the signal, is at 512 nm. The idler output beam is thus at 341 nm. In this figure, we can see the total power is conserved over the whole mixing process. Figure 3b shows how the spectral phase of the idler is affected for a linearly- and cubic varying input signal beam phase.

OUTLOOK

Our work on the S2E model for simulating pulse shaping, amplification, and upconversion in our photoinjector laser system demonstrates operational code that can be used for a number of applications including (inverse) designing a laser system, reverse engineering portions of an existing system, and tuning the system's performance parameters. We are currently using this model as part of a

ML-based approach to produce photoinjector laser pulse shapes employing programmable shapers in combination with advanced upconversion techniques. This S2E model will both help us determine optics and diagnostics as well as help determine limits on pulse shaping to avoid damaging our amplifier. Additionally, we will use the model to generate data sets to train ML networks to examine the relationship between generalized pulse shaping and electron beam and X-ray performance.

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