OPAL-FEL publication status and plans

stand July 2025

- Status summary
- Recap on relevant recent publications from SLAC on temporal (e.g. flattop) shaping
- Collection of ideas from different WPs

Project OPAL-FEL related publications

Type	Event	Title	Authors	Status
Proceeding	IPAC'25	NOVEL PHOTOINJECTOR LASER PROVIDING ADVANCED PULSE SHAPING FOR FLASH AND EUXFEL	Ilia et al.	online
Proceeding	Photonics West'25	Advanced pulse shaping for photoinjector lasers	Ilia et al.	online
Proceeding	CLEO/Europe-EQEC'25	Temporal Shaping of UV Picosecond Pulses for Photoinjectors	Ilia et al.	online
Proceeding	Europhoton'24	Novel Photocathode Lasers for the Hard- and Soft-X-ray Free Electron Lasers EuXFEL and FLASH	Mahnke et al.	online
Proceeding	IPAC'24	Characterization of low-emittance electron beams generated by a new photocathode drive laser system NEPAL at the European XFEL	Chen et al.	online
Proceeding	FEL'24	Novel Photocathode Lasers for the Hard- and Soft- X-ray Free Electron Lasers EuXFEL and FLASH	Mahnke et al.	accepted
Proceeding	FEL'24	BEAM DYNAMICS STUDY ON LOW-EMITTANCE ELECTRON BEAMS GENERATED VIA A COMBINED TRANSVERSE AND TEMPORAL PHOTOCATHODE LASER SHAPING APPROACH AT THE EUROPEAN XFEL	Cai et al.	accepted
Poster	ICFA WS'25	Machine Learning driven beam emittance optimization at EuXFEL	Ilia et al.	online
Poster	MT3'25	Optimizing EuXFEL Photoinjector Performance via Laser Shaping Approach	Klemps et al.	online
Code	zenodo	ASTRA-WEB	Klemps et al.	online
Report	zenodo	OPAL-FEL EuXFEL Photoinjector Simulation Data	Klemps et al.	online
Report	zenodo	OPAL-FEL EuXFEL NEPAL Frontend Simulation Data	Klemps et al.	online

SLAC flattop shaping journal publication in 2022

PHYSICAL REVIEW ACCELERATORS AND BEAMS **25,** 013401 (2022)

Temporal shaping of narrow-band picosecond pulses via noncolinear sum-frequency mixing of dispersion-controlled pulses

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A long-sought-after goal for photocathode electron sources has been to improve performance by temporally shaping the incident excitation laser pulse. The narrow bandwidth, short wavelength, and picosecond pulse duration make it challenging to employ conventional spectral pulse shaping techniques. We present a novel and efficient intensity-envelope shaping technique achieved during nonlinear upconversion through opposite-chirp sum-frequency mixing. We also present a numerical case study of the linac coherent light source-II photoinjector where transverse electron emittance is improved by at least 25%.

DOI: 10.1103/PhysRevAccelBeams.25.013401

- Simulation paper without measurements
  - Laser shaping method and simulations
  - Injector simulations

Temporal shaping of narrow-band picosecond pulses via noncolinear sum-frequency mixing of dispersion-controlled pulses

SLAC flattop shaping journal publication in 2022 (cont'd)

Dispersion controlled nonlinear shaping (DCNS) method & laser simulations (no measurements)

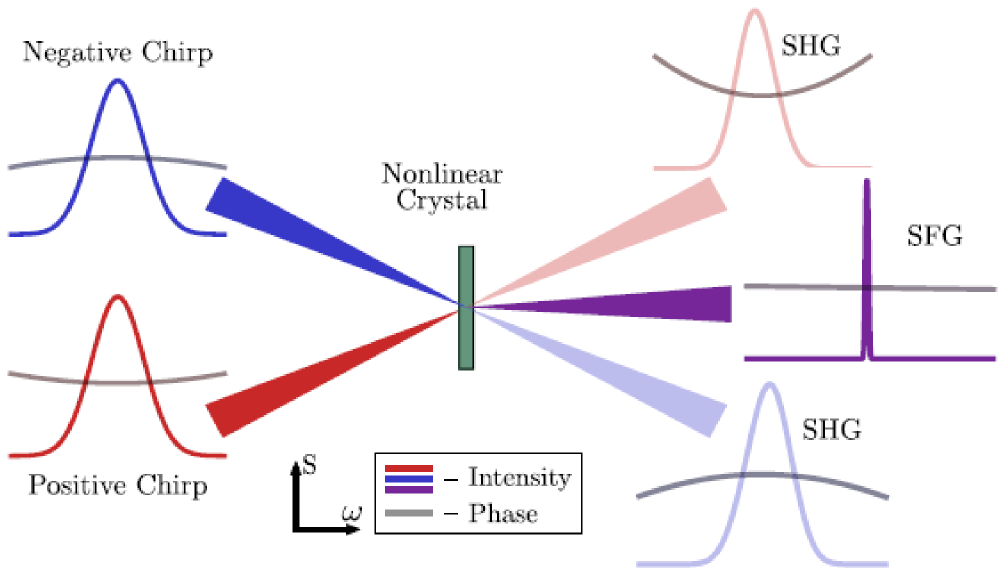

FIG. 1. DCNS method in the spectral domain demonstrating two pulses of equal on opposite chirp mixing in a nonlinear medium to generate chirped second harmonic (SHG) copies of each pulse along with the narrow band, flat phase, sum frequency (SFG) pulse.

SLAC flattop shaping journal publication in 2022 (cont'd)

Injector simulations using shaped electron bunches (no measurements)

conversion using highly dispersed pulses. In the case of linear accelerators and XFELs such the LCLS-II, this simple solution is expected to improve electron emittance across all investigated bunch lengths over conventional Gaussian pulses with an upward of 30% emittance reduction at short bunch lengths (0.25 mm) and 25% at bunch lengths greater than or equal to 1 mm. With an effective conversion efficiency of upward of 40%, we have laid a realistic avenue to substantially extend the brightness of photoinjector systems worldwide without major configuration changes and thus enhance current scientific capabilities on existing accelerators and reduce the cost of future accelerator facilities.

Main conclusion of the paper

- Injector simulations suggesting 25-30% reduction in transverse projected emittance
- Improved laser conversion efficiency to 40% by using DCNS

SLAC flattop shaping journal publication in 2025

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Full Length Article

Simulation of nonlinearly shaped UV pulses in LCLS-II

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ABSTRACT

Photoinjectors and Free Electron Lasers (FEL) are constantly advancing systems in accelerator physics. Improving these systems has pushed the boundaries of emittance and x-ray peak power available to the scientific community. In this paper, laser shaping at the cathode is proposed to further lower the emittance and flatten longitudinal electron beam profiles, which would result in brighter x-ray production. Using dispersion controlled nonlinear shaping (DCNS), laser pulses and beam dynamics were simulated in LCLS-II. The photoinjector emittance was optimized and the resulting e-beam profiles were then simulated and optimized in the linac. Finally, the expected FEL performance is estimated and compared to the current technology: Gaussian laser pulses on the cathode. The e-beams produced by DCNS pulses show a potential for 35% increase in x-ray power per pulse during SASE when compared to standard Gaussian laser pulses.

- **Still a simulation paper**
  - Injector optimization
  - Linac and FEL simulation (a few cases chosen from the injector)

Simulation of nonlinearly shaped UV pulses in LCLS-II

SLAC flattop shaping journal publication in 2025

still ~same DCNS laser shaping method as in 2022

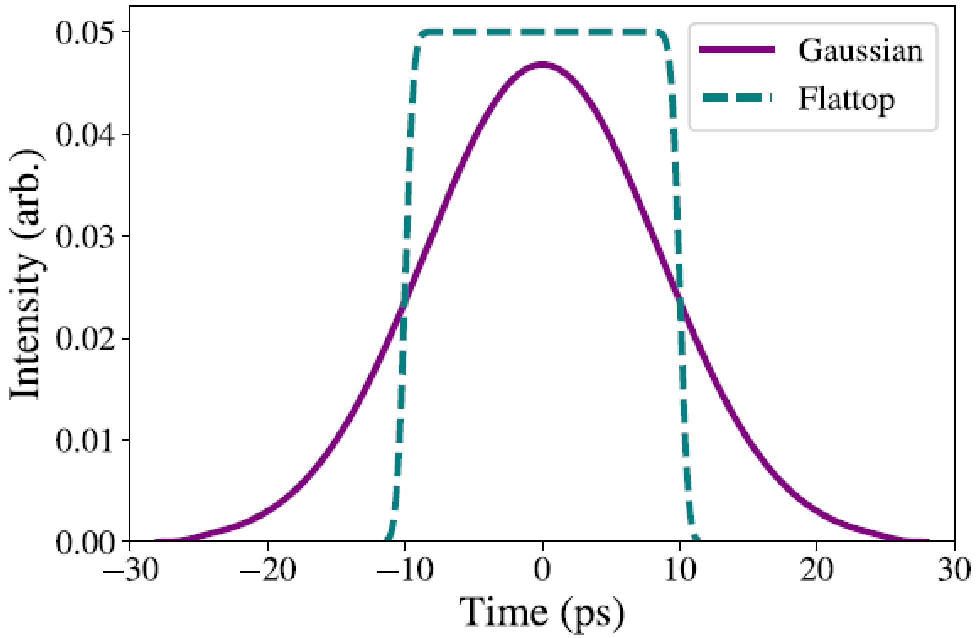

Fig. 1. Typical Gaussian and flattop laser profiles used in simulations of LCLS-II.

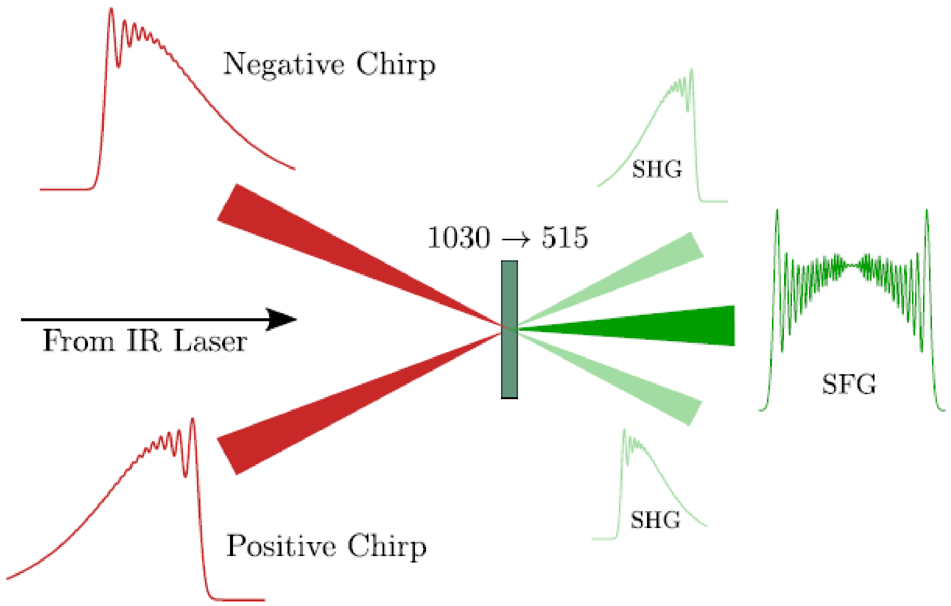

Fig. 2. Sum-frequency generation of a long optical pulse with shaped temporal intensity profile from highly dispersed short pulses. Temporally flattop pulses at 515 nm are generated in a non-colinear geometry from 1030 nm pulses with tailored phase.

SLAC flattop shaping journal publication in 2025 (cont'd)

still ~same DCNS laser shaping method as in 2022

6. Conclusion

In this paper, the UV laser shaping technique, Dispersion Controlled Nonlinear Shaping (DCNS), is reviewed and proposed for UV laser pulse shaping on photocathodes. Both the transverse and longitudinal shaping of UV pulses greatly impacts electron beam properties in photoinjectors and FELs. Gaussian and DCNS laser pulses were generated in simulation. The simulated UV pulses were then used in accelerator simulations as laser pulses on the LCLS-II photocathode. The resulting e-beams were then simulated in the injector and linac of LCLS-II. For both the Gaussian and DCNS case, the laser pulse shapes were included as optimization variables along with magnets and phases for the injector and linac to ensure a fair comparison. Optimization results indicate

Conclusion points:

- same laser shaping method "reviewed"

SLAC flattop shaping journal publication in 2025 (cont'd)

still ~same DCNS laser shaping method as in 2022

DCNS pulses can reach lower emittances at the exit of the injector. The DCNS pulses were also able to reach higher peak currents in the linac after optimization of the linac phases, chicanes, and laser heater.

Two optimized beam distributions, one Gaussian and one DCNS, were chosen for a basic FEL comparison. As expected, there is no appreciable difference in the time to saturation or SASE power generation. However, when the amount of charge at low emittance is taken into account, it is estimated that 74 pC vs 89 pC out of 100 pC contributed to lasing in the Gaussian and DCNS cases respectively. Using the variable gap of the undulators to set photon energy, the potential X-ray energy per pulse in the DCNS case is estimated to be 35% higher than the Gaussian case (2.6 mJ compared to 1.9 mJ). Given the lower slice emittance values for the DCNS beam in this case, there may be potential to lower gain length in certain parameter regimes. If the gain length can be lowered through emittance manipulation, saturation could be reached in some regimes. The flatness of the DCNS beam core (*i.e.* low chirp), could also contribute desired features in SASE photon beams, such as reduced bandwidth and higher spectral brightness.

Note, the comparison cases shown here were not optimized for FEL power, instead the focus of this paper was comparing a practical operating condition given changes to the laser profile at the cathode. The density of simulation points near the optimized cases, both at the end of the injector (Fig. 5) and the linac (Fig. 8), indicates the performance shown here could be achieved with tolerable amounts of jitter in the machine. Further optimizations of both the injector and linac may be able to reach higher peak currents.

In conclusion, DCNS is a promising method for emittance reduction and improved FEL performance. By updating laser optics, accelerator facilities may access lower emittance regimes. Longitudinal control of the photocathode laser can lead to better beam dynamics and in the case of LCLS-II, improved FEL performance.

- Injector optimization simulation repeated basically
- **(not in 2022 paper) FEL simulations showing 35% higher intensity than Gaussian pulses for the selected case**

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Highlights collection from WPs

- WP A: Laser shaping
- WP B: photoinjector optimization
- WP C: machine learning