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NOVEL PHOTOINJECTOR LASER PROVIDING ADVANCED PULSE SHAPING FOR FLASH AND EUXFEL

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Abstract

We recently commissioned the Next GenerAtion Photocathode Laser system (NEPAL) in Hamburg's XFEL facilities (FLASH and EuXFEL) and at DESY's Photoinjector Test Facility (PITZ). The system delivers deep UV pulse trains up to 1 ms long at repetition rates as high as 4.5 MHz and provides temporal and spatial shaping capabilities and individual amplitude control for bunch charge manipulation. The shaping features enable the generation of low emittance electron beams, which are essential for all XFELs and especially for extending the EuXFEL X-ray photon energy beyond 25 keV and for future high duty cycle upgrades which need to rely on lower gradient electron guns. Spatial shaping is achieved via a beam shaping aperture, which truncates the gaussian laser beam shape. Temporal shaping is achieved in the Fourier space by manipulating the laser's spectrum and generating bandwidth limited laser pulses. It is implemented by a high-resolution spatial light modulator in the near-infrared driver laser, allowing precise spectral amplitude and phase control of UV pulses. In this contribution we present advanced control schemes that pre-compensate for laser nonlinearities and initial experimental results at EuXFEL. We demonstrate UV flat-top pulse profiles generation with durations ranging from 10ps to 20ps and show that they can be transferred onto the electron beam. This achievement represents a significant step toward emittance optimization at EuXFEL and will expand the facility's operational energy range in the near future.

INTRODUCTION

Photocathode lasers play a crucial role in the generation of electrons for XFELs, effectively defining the performance boundaries within which these systems can operate. For this reason, DESY has been continuously improving the photoinjector systems used in its FEL facilities, aiming to provide all the necessary features for operation along with the high reliability required for continuous service.

The last iteration of photocathode lasers is NEPAL (NExt generation PhotocAthode Laser), which was commissioned last year and operational since [1]. The system is now in use with a total of five identical units deployed at FLASH, EuXFEL, and the Photoinjector Test Facility (PITZ).

NEPAL has been designed to fulfill both current and future requirements of photocathode laser systems, offering the following features:

- Reliable and stable operation for FEL facilities, delivering deep UV bursts lasting up to 1 ms, with pulse energies of several μJ at intra-burst repetition rates of up to 4.5 MHz.
- Precise control over burst-envelope shaping and fine-tuning of individual pulse energies.
- Dual-laser configurations to support advanced FEL operation modes.

In addition, it provides as a core feature the delivery of temporally and spatially shaped laser pulses, enabling tailored electron bunch generation aimed at reducing emittance with respect to the previously used Gaussian temporal pulse shape. Controlling the initial electron distribution at the photocathode reduces space-charge effects, ultimately lowering beam emittance — a critical improvement for extending XFEL capabilities toward higher photon energies and higher duty cycles [2], supporting a wide range of cutting-edge scientific applications.

In this paper, we describe the architecture and core functionalities of the NEPAL system, detail the temporal pulse shaping approach based on a high-resolution spatial light modulator (SLM), and present results from its first experimental deployment at EuXFEL, where shaped UV pulses were successfully transferred to the electron beam.

PHOTOCATHODE LASER PULSE SHAPING

The NEPAL laser system architecture which is detailed in [1], is schematically shown here in Fig. 1. The laser front-end consists of a Yb-fiber mode-locked oscillator, a passive fiber stretcher, a fiber-coupled SLM, and Yb-fiber amplifiers, which produce a pulse train centered at a wavelength of 1030 nm. The output is subsequently amplified by a Yb:YAG power amplifier, which, after compression, drives a two-stage second harmonic generation process using LBO and BBO crystals to convert the laser to a wavelength of 257.5 nm. Additionally, a separate Yb-fiber amplifier generates 150 fs pulses at 1030 nm to characterize the UV

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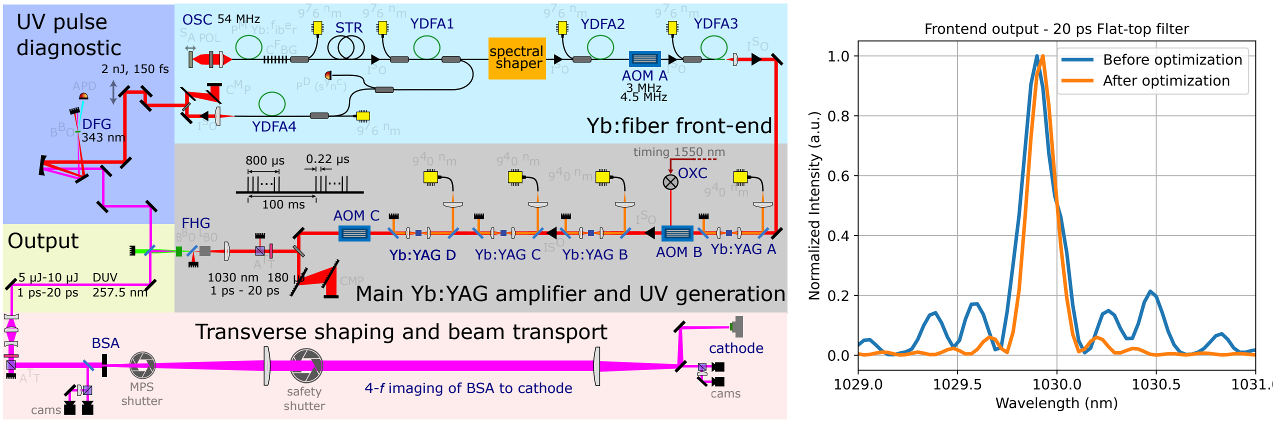

(a) (b)

Figure 1: (a) Schematic of the NEPAL laser. OSC: oscillator; SA: saturable absorber; POL: polarizer; CFBG: chirped fiber Bragg grating; STR: passive fiber stretcher; ISO: isolator; YDFA: pm-Yb:fiber amplifier; CMP: transmission grating compressor; Yb:YAG: Yb:YAG rod amplifier; PD: photodiode; AOM: acousto-optical modulator; OXC: optical cross-correlator; APD: avalanche photodiode; FHG: Fourth harmonic generation; BBO: beta-Barium borate; LBO: Lithium triborate; DFG: difference frequency generation; ATT: attenuator; BSA: beam-shaping aperture; MPS: machine protection system; cams: camera-based beam-stabilization; cathode: CsTe photocathode at the XFEL gun. (b) Comparison of spectral output from the laser front-end before and after optimization, showing significant reduction in distortions caused by SPM.

output through difference frequency generation (DFG) cross-correlation. The generated electron bunch charge at the photocathode is controlled by two key elements: a polarizer-waveplate combination for slow bunch-charge feedback and an acousto-optical modulator (AOM) for individual pulse-picking. The AOM ensures a flat electron-bunch train charge or enables arbitrary charge patterns for special operation modes. Synchronization of the UV pulses with the accelerator RF phase and the requested electron-bunch pulse pattern is achieved by phase-locking the oscillator to the facility's main RF oscillator, while slow time drifts are corrected using an optical cross-correlator signal linked to the facility-wide pulsed-laser timing system [3].

Spatial shaping is achieved using a set of variable apertures imaged onto the photocathode, while temporal shaping is provided by the SLM, which functions as a high-resolution spectral shaper, enabling precise amplitude and phase modulation.

However, Fourier-based temporal pulse shaping is not straightforward due to system nonlinearities, such as self-phase modulation (SPM), gain narrowing, and fourth harmonic generation (FHG), which inevitably distort the pulse. To mitigate these effects, efforts have focused on reducing SPM in the fiber front-end by optimizing fiber lengths and core sizes, and by balancing gain across the amplifier stages. The impact of these improvements on the spectral output is illustrated in Fig. 1(b).

At this stage, the integration of numerical simulations with experimental measurements enables an iterative optimization process as illustrated in Fig. 2. Using this approach we successfully generated temporal flat-top profiles [4], which are recognized as optimal for emittance reduction in EuXFEL [5–7].

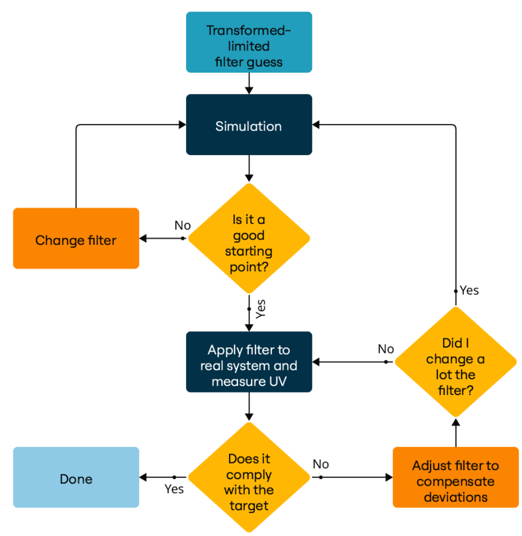

Figure 2: Flowchart of the iterative pulse shaping process using a SLM. The process starts with a transform-limited filter guess, followed by simulation and experimental feedback, refining the filter until the desired UV output is achieved.

RESULTS

We have successfully demonstrated generation of flat-top UV pulse profiles with the photocathode laser systems operating in EuXFEL (NEPAL X1 and X2) as shown in Fig. 3(a). This achievement highlights the transferability of the shaping process between different NEPAL systems, ensuring consistent performance across multiple installations. To evaluate the robustness of the shaping process, stability tests were conducted over a week-long period. The

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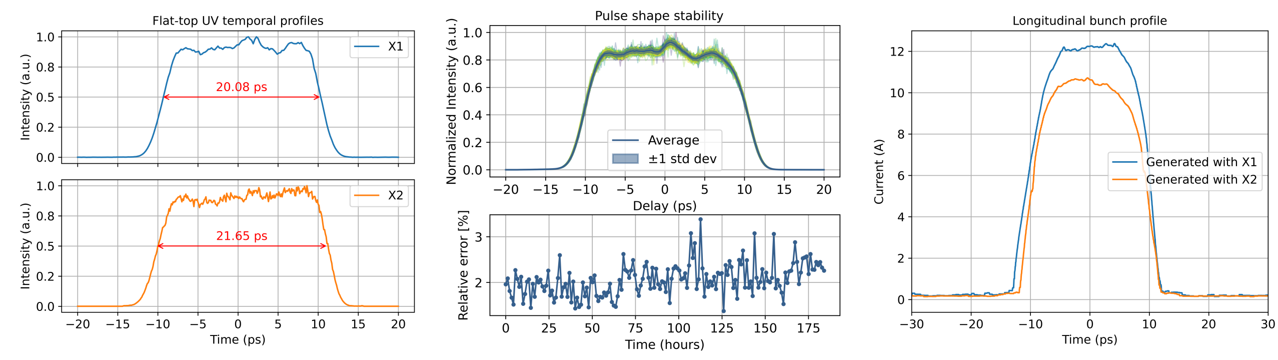

(a) (b) (c)

Figure 3: (a) Temporal profiles of the UV laser pulses, measured with DGF cross-correlator. (b) Temporal stability of pulse shape over 1 week. (c) Electron bunch profiles measured after injector in EuXFEL, at 250 pC charge.

results, shown in Fig. 3(b), indicate that the intensity profile remains stable within a few percentage points, with the temporal shape remaining consistent throughout the entire pulse train. This stability ensures reliable operation for extended periods, as required for high-duty-cycle FEL facilities. Electron bunches were generated using both NEPAL X1 and X2 lasers, and their profiles were characterized after the injector. The temporal pulse profile was successfully transferred to the electron beam, as illustrated in Fig. 3(c). While the flat-top shape was preserved at lower bunch charges, higher charges (e.g., 250 pC) exhibited space-charge effects, leading to slight distortions in the profile. Measurements of the transverse projected emittance for flat-top (FT) laser profiles at 250 pC showed promising results, with $\varepsilon_{xy} = 0.480\,\mu\text{m}/0.325\,\mu\text{m}$ and mismatches of 1.17 and 1.42 for the X2 FT case. These values approach the estimated thermal emittance of $0.275\,\mu\text{m}$ for a 1 mm uniform distribution, indicating that about 70% of the total emittance originates from the cathode and the remaining 30% from factors such as space-charge effects and transverse laser non-uniformities. Slice emittance measurements (Fig. 4) confirm that the flat-top temporal profile produces a significantly flatter emittance distribution compared to a Gaussian profile. The central slice level remains sensitive to both temporal shaping and transverse laser intensity non-uniformities

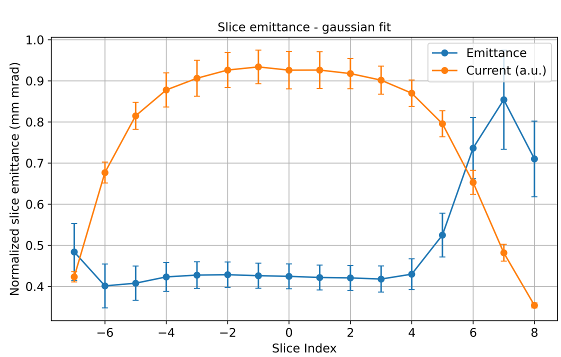

Figure 4: Slice emittance ε_x after injector for NEPAL X2 with a temporal FT and spatial truncated gaussian profile (1 mm spot size) at 250 pC charge and 130MeV energy.

caused by the convolution of the laser intensity with the cathode QE map. Achieving further improvements in emittance thus requires not only temporal but also better transverse laser profile control, along with a deeper understanding of their interaction with accelerator and injector dynamics. Finally, following the successful stability tests, shaped laser pulses with flat-top profiles were deployed for user experiments at EuXFEL. This marks a significant milestone, as the shaped pulses are now being used in routine operation, enabling advanced FEL modes and supporting cutting-edge scientific applications.

CONCLUSIONS

The NEPAL laser systems have been successfully deployed as photoinjector lasers at EuXFEL, FLASH, and PITZ, with five systems collectively delivering over 10,000 hours of stable beam operation in 2024/2025. These systems have demonstrated robust performance, meeting the demanding requirements of high-duty-cycle FEL facilities.

Research and development efforts on advanced UV pulse shaping for emittance reduction have shown promising results. Bunch shaping has been successfully demonstrated at EuXFEL and PITZ, with shaped laser pulses effectively deployed in user experiments. These achievements underline the capability of the NEPAL systems to enable tailored electron bunch generation, critical for improving beam quality and extending FEL operational capabilities. Additional tuning and experimental time with the accelerator and injector will be essential to refine the process and achieve optimal performance. To further enhance performance, a machine learning framework is under development to automate the pulse shaping process and optimize emittance. This approach aims to support future XFEL upgrades, enabling higher photon energies and high-duty-cycle operation, thereby expanding the scientific reach of these facilities.

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