GRADIENT-BASED LASER CONTROL FOR END-TO-END PHOTOINJECTOR EMITTANCE OPTIMIZATION AT EUXFEL

D. Ilia[1,2]* A. Aksoy[3], Z. Amirkhanyan[3], F. Brinker[1], M. Cai[1,2], M. E. Castro Carballo[1], Y. Chen[1],
J. Good[1], M. Gross[1], U. Große-Wortmann[1], M. Guetg[1], I. Hartl[1], W. Hillert[2], Y. Jiang[1],
M. Kerstan[1], A. Klemps[4], M. Krasilnikov[1], J. Kwasniok[1], C. Li[1], X. Li[1], C. Mahnke[1],
C. Mohr[1], C. Mustapha[3], A. Oppelt[1], S. Pakluea[3], H. Panuganti[1], F. Pressacco[1], C. Richard[1],
F. Stephan[1], A. Tavakol[1], H. Tünnermann[1], G. Vashchenko[3], D. Villani[3], D. Xu[1], S. Zeeshan[1]
[1]Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany
[2]Universität Hamburg, Hamburg, Germany
[3]Deutsches Elektronen-Synchrotron DESY, Zeuthen, Germany
[4]Hamburg University of Technology, Hamburg, Germany

Abstract

Achieving low emittance at the photoinjector is essential for meeting the performance targets of the European XFEL, particularly for high photon energies and future high-duty-cycle operation. Both the temporal structure of the drive-laser pulse and the RF-gun settings contribute significantly to the final beam quality, yet their optimization is complicated by strong nonlinearities in the laser system and complex gun response. We have developed a differentiable, physics-based model of NEPAL, the photoinjector laser of EuXFEL, that enables gradient-driven optimization of the temporal UV pulse shape. The model captures the relevant nonlinearities of the optical chain and allows direct optimization of spectral amplitude and phase to obtain target UV profiles at the photocathode. In parallel, a machine-learning surrogate model is being implemented to optimize the RF-gun operating parameters. Together, these tools provide an end-to-end control framework for emittance reduction at EuXFEL. Initial results demonstrate that the differentiable model enables accurate temporal UV pulse shaping at EuXFEL. Work is ongoing to integrate this approach with ML-assisted gun optimization within the proposed end-to-end control framework.

INTRODUCTION

The performance of X-ray free-electron lasers (XFELs) depends critically on the quality of the electron beam, with the transverse emittance being a key figure of merit. At EuXFEL, reducing the transverse emittance is a primary focus of ongoing development, as it enables operation at higher photon energies [1] and will support the future transition to high-duty-cycle operation. Alongside thermal emittance, space charge is one of the dominant contributions to the bunch emittance, and it can be mitigated by shaping in space and time the photoinjector laser pulses to control the initial electron bunch distribution. In previous work [2, 3], we reported on NEPAL, the photoinjector laser serving EuXFEL, FLASH, and PITZ, which supports both temporal and spatial shaping. In particular, we demonstrated UV flat-top pulse shaping via spectral amplitude and phase control with a spatial light modulator (SLM) in the laser IR front-end. The shaping was achieved through an iterative procedure combining simulation and experimental feedback, and once transferred to the electron beam it produced a measurable impact on the slice emittance. This scheme is, however, entirely manual and heuristic, making the outcome operator-dependent and difficult to reproduce. The underlying difficulty is the optical chain mapping SLM settings to the UV profile, which contains several strongly nonlinear stages and admits no direct analytical inversion. As a result, the manual scheme is too slow and irreproducible to support systematic emittance studies, let alone end-to-end optimization of the gun parameters. In this paper we address this by introducing an automated, gradient-based shaping algorithm that removes the operator dependence and allows for arbitrary shaping, bringing us one step closer to end-to-end optimization of the emittance. We demonstrate accurate temporal UV pulse shaping at EuXFEL, which has already been used operationally for twin-bunch FEL operation. We further deploy the method at PITZ to study the dependence of the emittance on the pulse profile, showing how temporal shaping can now be exploited for systematic exploration and integration with optimization methods targeting the gun parameters.

PHOTOCATHODE LASER TEMPORAL SHAPING

NEPAL delivers picosecond deep-UV pulses at 257 nm to the photocathode through a chirped-pulse amplification (CPA) scheme followed by two stages of frequency conversion (Fig. 1(a), top). Temporal pulse shaping is enabled by a fiber-coupled spatial light modulator (SLM) in the IR front-end, which provides both amplitude and phase control in the spectral domain. The temporal profile impressed at this stage is, however, distorted as the pulse undergoes amplification and propagates through the two nonlinear conversion stages. Moreover, these coupled nonlinear effects preclude a direct, analytical mapping from front-end settings to the UV profile. We therefore formulate the shaping task as an optimization problem: find the spectral filter $u(\nu)$ such that the resulting intensity profile $I_{\mathrm{laser}}(t)$ matches a given

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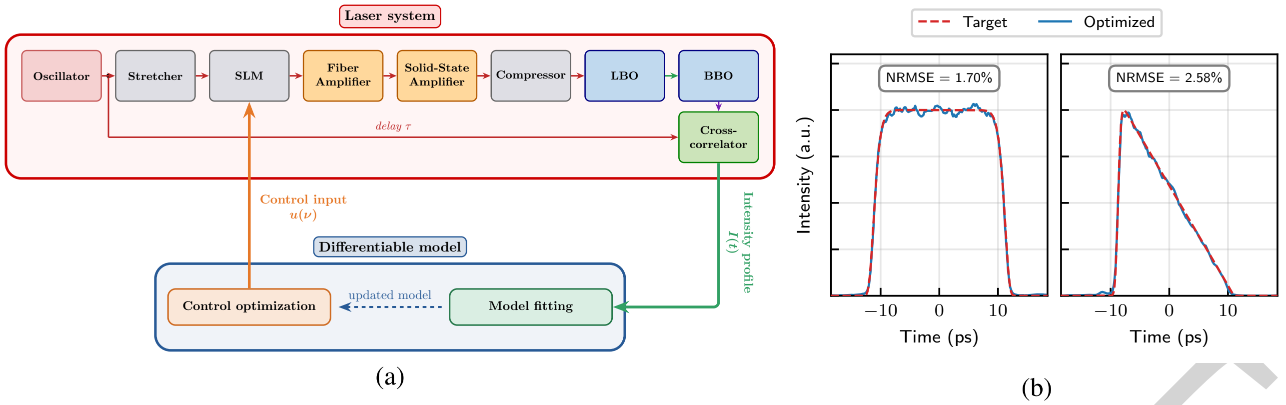
* denis.ilia@desy.de



(a)

(b)

Figure 1: (a) Schematic of the adaptive shaping scheme. Top: the NEPAL laser chain. Bottom: the differentiable model of the laser, used in two alternating gradient-based loops: model fitting, which fits the model parameters to the measured intensity $I(t)$, and control optimization, which updates the SLM control input $u(\nu)$ using the refined model. (b) Results of temporal shaping of two picosecond UV profiles.

target. Black-box optimization methods have been applied to similar problems [4], but typically require thousands of measurement cycles to converge on a single profile, which is incompatible with routine photoinjector operation and would prevent systematic emittance studies.

We instead introduce a differentiable model of the laser system, $f(u, \theta) = I_{\text{model}}(t)$, on which gradient descent in u efficiently locates the optimal filter; we refer to this step as control optimization. Its success hinges on the model being a faithful local description of the real system. We therefore tune the model parameters via a second gradient-based loop, model fitting, in which θ is adjusted so that the simulation reproduces measurements taken on the real laser. The feedback for this loop is provided by a cross-correlator that samples the UV pulse with a 150 fs gate. Alternating control optimization and model fitting (Fig. 1(a), bottom) thus yields an adaptive algorithm that converges in a small fraction of the iterations required by black-box methods. We have applied the full scheme at EuXFEL: as shown in Fig. 1(b), the method reproduces the target profiles with a normalized RMS error below 5 % and converges in about 50 iterations — more than an order of magnitude fewer than typical black-box approaches at comparable accuracy. In wall-clock terms, a complete shaping cycle now takes about four hours rather than several days, making the method usable on an operational basis and, most importantly, enabling systematic studies of how temporal shaping affects the electron-beam emittance.

TEMPORAL SHAPING FOR FEL APPLICATIONS

The ability to shape the photocathode laser pulse in time opens up several routes to improving FEL performance. On the one hand, it provides direct control over the initial longitudinal electron distribution at the gun, and therefore over the space-charge contribution to the emittance. On the other hand, it enables operational modes that rely on a tailored pulse shape, including schemes recently proposed for plasma-wakefield acceleration and attosecond XFEL pulses [5–7]. Below we present two recent application cases: an operational deployment at EuXFEL and a systematic emittance study at PITZ.

EuXFEL is served by two photoinjector lasers, whose temporal profiles should in theory match if the same spectral filter is used but in practice differ enough to require dedicated tuning when switching between them. Using the shaping scheme described above, we match the two profiles (Fig. 2(a)), enabling seamless transitions during operation without additional tuning time. The same capability also makes twin-bunch operation practical, in which both lasers are used to generate interleaved electron bunches that generate self-amplified spontaneous emission (SASE) at the undulators (Fig. 2(b)).

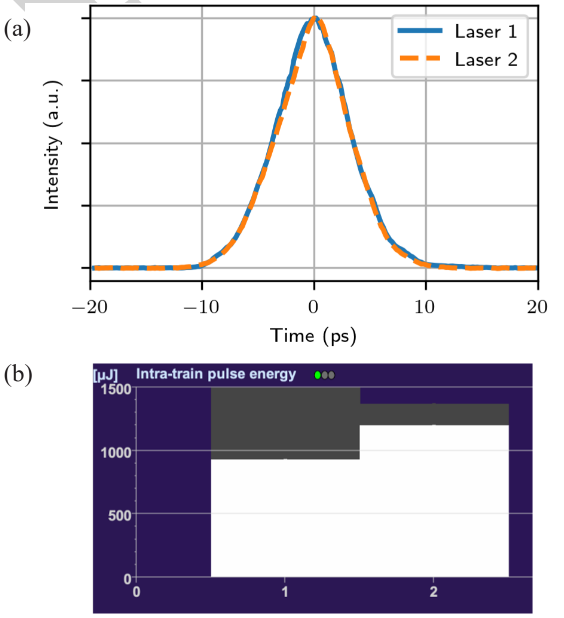


Figure 2: (a) Matched temporal profiles of the two photoinjector lasers at EuXFEL. (b) Twin-bunch operation enabled by the matched lasers: both bunches are generating SASE.

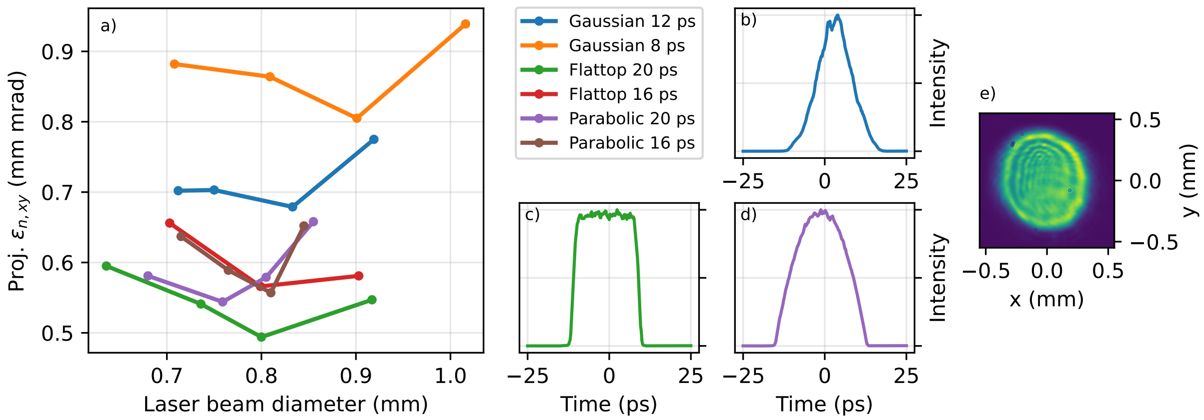


Figure 3: Transverse emittance dependence on photocathode laser pulse profile and spot size. (a) Projected normalized emittance measured at PITZ for the temporal profiles indicated in the legend as a function of laser spot size. (b-d) Measured temporal profiles used in the study (durations given as FWHM), respectively Gaussian 12 ps, flat-top 20 ps, parabolic 20 ps. (e) Laser transverse profile at 0.8mm diameter.

While temporal shaping has clear operational use cases, our main motivation here is to investigate how the emittance depends on the initial distribution. As part of the emittance optimization program for EuXFEL, we carried out a dedicated study at the Photo Injector Test Facility at DESY Zeuthen (PITZ) to evaluate this dependence systematically. Although the full analysis is still ongoing, we report here preliminary results on the transverse emittance as a function of both the temporal profile and the laser spot size.

Figure 3 shows the normalized transverse emittance at 250 pC for several combinations of spot size and temporal profile, from which a few clear trends emerge. First, shorter pulses systematically yield higher emittance, consistent with the increased role of space-charge forces at higher peak current. Second, for each temporal profile the emittance exhibits a minimum at a different spot size, reflecting the expected trade-off between space-charge and thermal contributions. Notably, flat-top pulses appear to yield a lower emittance than parabolic pulses of equal FWHM duration. While a complete analysis of the data and associated uncertainties is still pending, re-measurement of the same operating point one week later returned a consistent value, hinting at a possible benefit of flat-top shaping [8].

CONCLUSIONS

We have presented an adaptive, gradient-based scheme for temporal shaping of the NEPAL photocathode laser, based on a differentiable model of the laser system. The method achieves picosecond UV profiles with a normalized RMS error below 5 % in about 50 iterations, making temporal shaping practical on an operational basis. At EuXFEL, this enables matching of the X1 and X2 photoinjector laser profiles for seamless switching and twin-bunch lasing.

Beyond this operational application, we used this capability to investigate how the transverse emittance depends on the initial laser distribution. A preliminary study at PITZ as a function of pulse profile and spot size suggests a possible advantage of flat-top over parabolic shaping at equal FWHM and provides a first indication of how the temporal profile contributes to the emittance. Ongoing work focuses on a deeper analysis of these data, including a full assessment of measurement uncertainties, and their integration with start-to-end simulations, with the goal of disentangling the various contributions to the emittance and informing further optimization at EuXFEL. In parallel, we are extending the shaping scheme to the laser's spatial profile, an equally important driver of the emittance, so that temporal and spatial degrees of freedom can be optimized jointly at EuXFEL.

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