ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPS77

# APPLICATIONS OF MACHINE LEARNING IN ULTRAFAST LASER CONTROL

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## ABSTRACT

Accurate adjustment of operational parameters is crucial for configuring a photoinjector to produce electron bunches with specific characteristics. The precision in modifying laser parameters is critical for extending the applications of photoinjectors. The interaction of the laser pulse with the photocathode significantly influences the electron bunch's 3D-phase-space. It is essential to independently manage aspects like the laser's transverse shape, energy, and timing profile, correcting any variations across different time scales. Generating varied laser intensity distributions allows for improved management of both the transverse and longitudinal emittance of electron bunches by influencing the space-charge forces. This study focuses on laser shaping, given that while the adjustment of downstream electron optics in an accelerator is well-established, optimizing laser parameters presents more challenges.

## INTRODUCTION

The transportation of a laser pulse to a photocathode is a complex process involving multiple optical elements that relay the pulse from its origin to the electron gun. Positioned strategically near the photocathode, shaping and diagnostic optics refine the laser's characteristics, essential for ensuring the longevity and robustness of copper photocathodes, which are favored in high-availability facilities due to their durability. These photocathodes generally operate with UV laser pulses having wavelengths from 250 to 300 nm, demanding precise optical manufacturing to meet the stringent tolerance requirements. A Spatial Light Modulator (SLM) is a sophisticated electronic apparatus designed to modulate the amplitude or phase of light waves across spatial and temporal dimensions (Refer figure 2). Fundamentally, an SLM serves as an advanced optical component capable of manipulating various light properties, typically utilized in synergy with lasers or other coherent light sources to achieve precise control over light behaviour. This system setup includes using a spatial light modulator (SLM) to adjust the intensity of the second harmonic of an ATF Nd:YAG laser at 532 nm, facilitating the optimization of the photocathode's laser profile through fourth harmonic generation and image relaying. Refer to Figure 3 for a detailed schematic of the SLM application. High beam currents in photoinjectors can disrupt the uniformity of the photocathode via ion bombardment, leading to significant variations in electron density [1]. Furthermore, even slight wavefront distortions, on the order of less than 15 nm, can cause modulations in laser intensity of over 10%, adversely affecting the emittance of electron bunches. Techniques like Fourier relay imaging are employed to mitigate these effects, maintaining stability in the laser pathway through a sequence of image planes, from amplifiers to harmonic generation crystals, before ultimately reaching the photocathode. The work by Li et al. (2017) [1] underscores the utility of ultraviolet laser transverse profile shaping in boosting the performance of X-ray free electron lasers. They utilized a digital micromirror device for precise control of a 253 nm laser, although the low UV damage threshold of this technology limits broader applications.

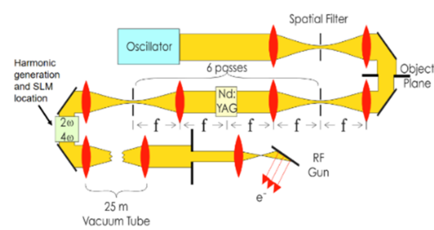


Figure 1: Facility configuration.

Alternatively, Maxson et al. (2015) [2] demonstrated how an SLM could effectively shape the beam of a dc photoemission gun, using a straightforward algorithm that yielded highly accurate laser profiles. This project seeks to harness a liquid crystal-based SLM for meticulous control over the transverse shape of a Nd:YAG laser's second harmonic, integrating real-time feedback to enhance shaping precision.


Figure 2: SLM.

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Recent innovations have further highlighted the importance of adaptive optics in compensating for optical aberrations, thereby enhancing beam quality in applications requiring high precision [3]. To tailor the laser profile for specific photoinjector and electron beam parameters effectively, we initiate a learning phase involving a neural network. The training comprises two principal approaches: capturing the photocurrent's image downstream—reproduced by magnetic optics to mirror the emission profile at the photocathode—and recording it for analysis with a phosphor screen and camera. This image analysis aids in assessing the correspondence between ideal and actual emission profiles, serving as a fitness function to refine the neural network [4, 5]. Concurrently, emittance scans are conducted to adjust the laser profile, utilizing the collected data as another fitness measure. These methodologies are evaluated for their synergistic potential and efficiency.

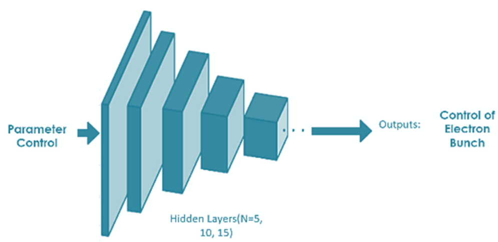


Figure 3: Surrogate model.

Our endeavor aligns with the objectives outlined in the strategic plan of the CBB, employing neural network-based controllers to optimize beam dynamics and control outcomes. The insights gained here are also applicable to the enhancement of beam control in electron microscopes and could be extended to MeV-class ultrafast electron diffraction systems.

## RESEARCH FOCUS

Our project is dedicated to advancing the control and precision of electron beam emittance through the integration of machine learning and sophisticated laser manipulation technologies, including the use of a spatial light modulator (SLM). This approach aims to refine the dynamic adjustment of laser parameters, essential for modulating the beam profile precisely and enhancing the quality and consistency of electron beams. Recent developments in adaptive optics have introduced promising techniques for precision in beam shaping that are crucial for achieving our project goals [7].

In collaboration with the Argonne Leadership Computing Facility, we are refining the electron gun model within the VSIM framework for the Brookhaven system. By linking extensive computational resources with the main ATF at BNL during experimental runs, we enable rapid model development and refinement, facilitating advancements in electron beam technology as illustrated in Figure 3.

The strategic placement of the SLM between the second and fourth harmonic generation crystals is a critical component of our research, allowing for the optimization of the device's efficiency and damage thresholds. This setup enables the conversion of a modulated green beam profile into UV, which is then precisely imaged onto the photocathode. Additionally, any higher-order energies deviating from the central beam are meticulously filtered out using an aperture or the limited acceptance angle of the fourth harmonic crystal.

Our investigations also extend to a detailed examination of the photoinjector's parameters, aiming to ensure robust and efficient laser shaping. This encompasses both theoretical and empirical studies focused on fine-tuning the laser pulse delivery mechanisms to the photocathode and optimizing the overall architecture of the shaping optics.

Central to our research is the development of a machine learning-driven model that effectively correlates input variables—such as photoinjector and electron beam parameters—with optimized laser shaping profiles. This model benefits from continuous enhancements through training on data collected from actual system operations, ensuring it can manage a vast array of variables and consistently predict optimal configurations. The impact of machine learning on optimizing photoinjector operations provides a solid foundation for our modeling strategies [8].

Ultimately, our project not only aims to refine current methodologies but also to make significant contributions to the field through scholarly articles. We anticipate the publication of one or two papers detailing our findings in the proceedings of highly reputable conferences or journals.

## FUTURE SCOPE

Moving forward, we aim to further refine our model's training processes to enhance its predictive capabilities. By doing so, we expect to more accurately determine the optimal input parameters for the photoinjector and electron beam, ensuring the best possible outcomes. This ongoing development is crucial for advancing our understanding and control of these complex systems, pushing the boundaries of what can be achieved in particle acceleration technology.

## ACKNOWLEDGEMENT

We gratefully acknowledge the financial support for this work provided by the U.S. National Science Foundation, under Award PHY-1549132, and the Center for Bright Beams. Their support has been instrumental in the progression of our research and the achievements we have made.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPS77

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