Contribution ID: **65** Type: **Poster**

Machine Learning driven beam emittance optimization at EuXFEL

Planned upgrades of the European X-Ray Free Electron Laser (EuXFEL) target higher photon energy and a high duty-cycle operation up to CW-operation using a superconducting RF gun with lower gradient. An operation in this regime though critically depends on improvements of the beam slice emittance of the electron gun. Within the OPAL-FEL project, we are addressing this challenge by developing a data-driven optimization framework for longitudinal drive laser shapes to minimize beam emittance, thereby ensuring the delivery of high-quality electron beams.

Our approach centers on the application of deep learning techniques to create an inverse model that predicts optimal parameter configurations for the photoinjector, enabling targeted control of beam emittance. This methodology involves generating synthetic training data through comprehensive beam dynamics simulations and introduces a machine learning-based strategy for temporal pulse shaping, accommodating a broad family of pulse distributions beyond flattop and Gaussian shapes.
We present results from trained neural networks with various architectures and establish a theoretical foundation for the invertibility of the forward model by connecting our approach to the theory of inverse problems. In particular, we draw on Whitney's embedding theorem within the framework of attractor reconstruction to validate model invertibility.

Leveraging extensive simulations, data-driven modeling and theoretical insights, our approach offers a robust pathway for improved optimization and control of photoinjector parameters in CW mode, with potential applications for further advancements in FEL performance.

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Session Classification: Poster session

Track Classification: Surrogate Modelling and Digital Twins