Machine-Learning for Injector Emittance Optimization.

OPAL-FEL - Optimized Laser Pulses for Free-Electron-Lasers

A. Klemps and M. Cai, on behalf of the OPAL-FEL team

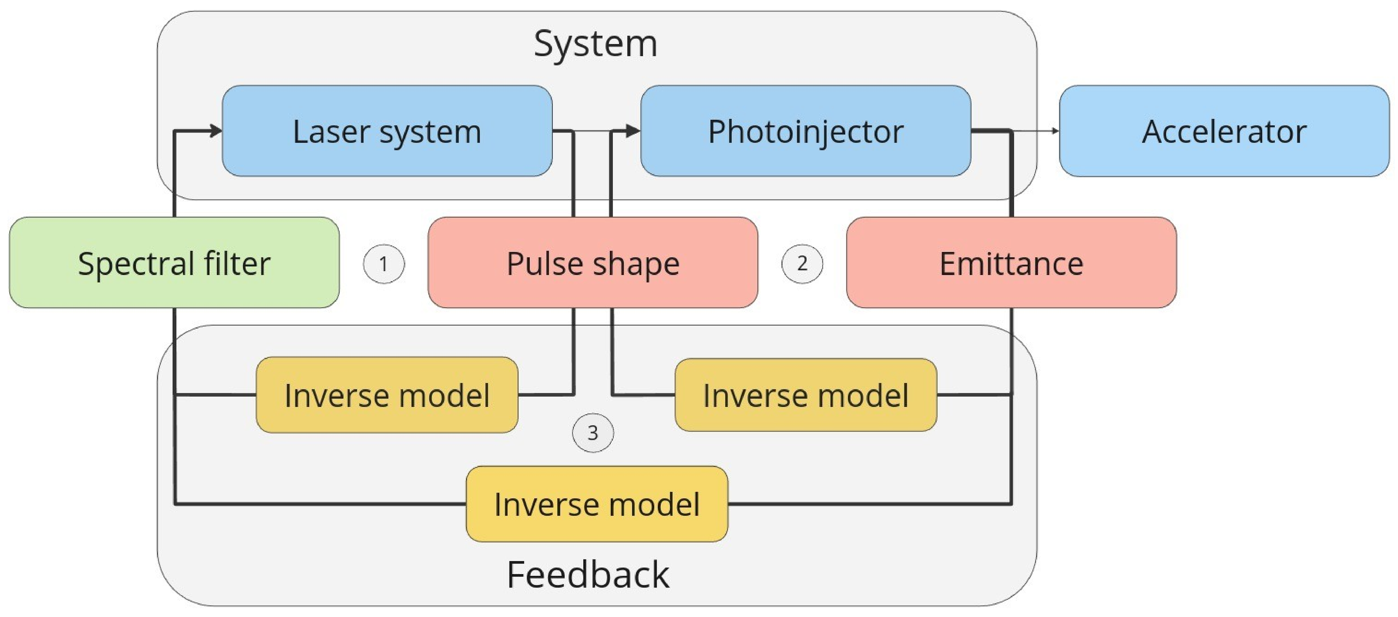
OPAL-FEL is developing innovative machine learning algorithms to optimize emittance by solving the complex problem of temporal cathode laser shaping. Preliminary simulations and results demonstrate promising outcomes, including the potential to reach photon energies even beyond 30 keV along with minimal emittance, accelerating XFEL upgrades towards successful HDC/CW operation and unlocking new frontiers in attosecond science and PWFA research.

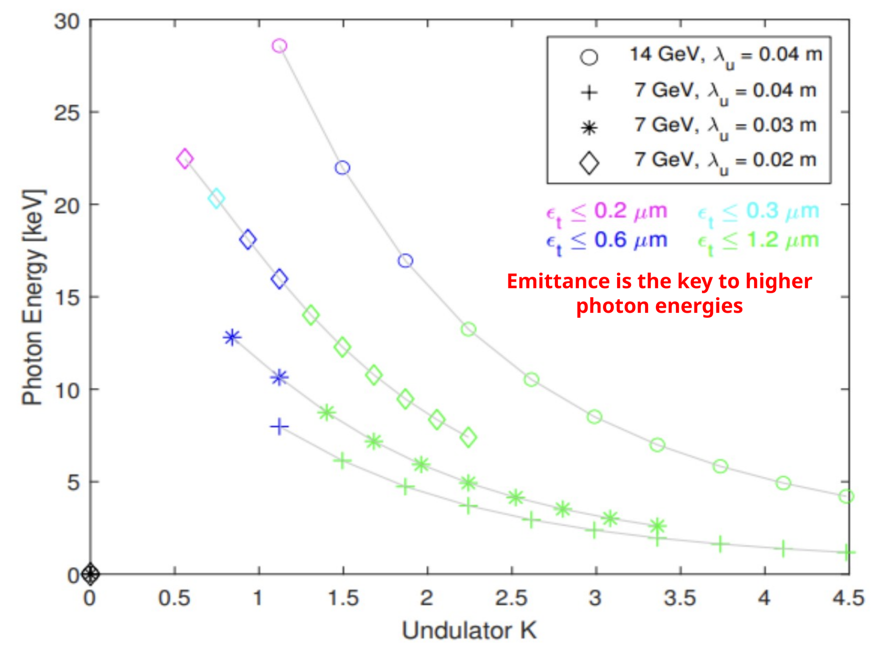
OPAL-FEL Project Structure and Ideas

Core Ideas

Use modern machine learning techniques for optimizing electron bunch emittance via laser pulse shaping, including:

- Developing laser shaping techniques
- Establishing digital twin based on physics models
- Inverse modeling for emittance optimization
- Conceptualizing multiplexed injector optimization for advanced applications

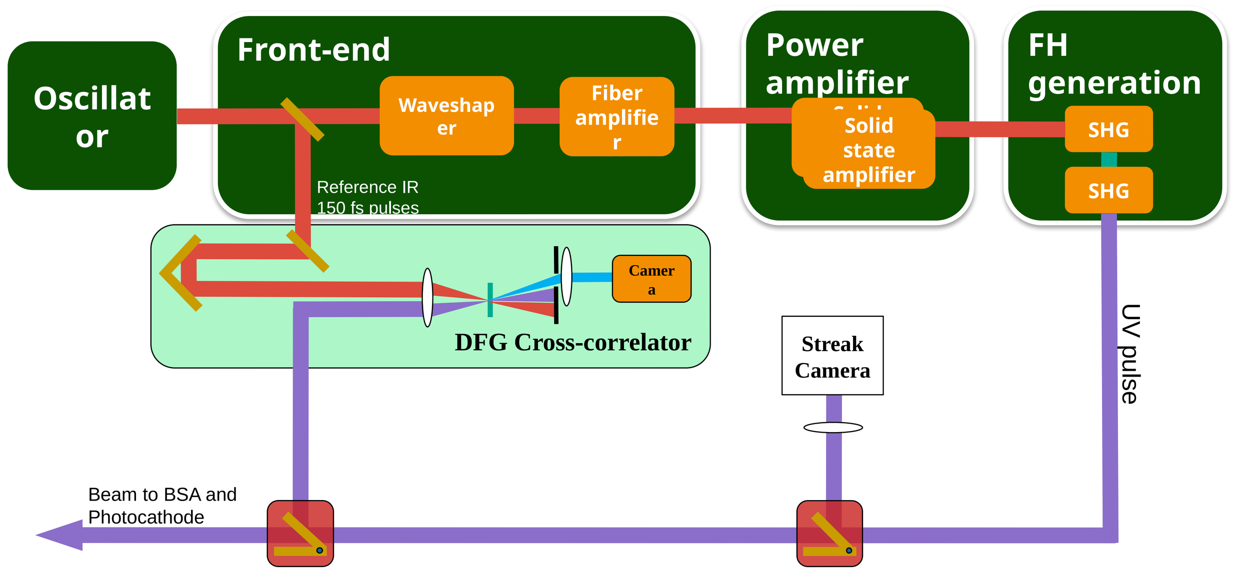




Pulse Shaping Enables Emittance Optimization for HDC/CW EuXFEL & Advanced Applications – by D. Ilia

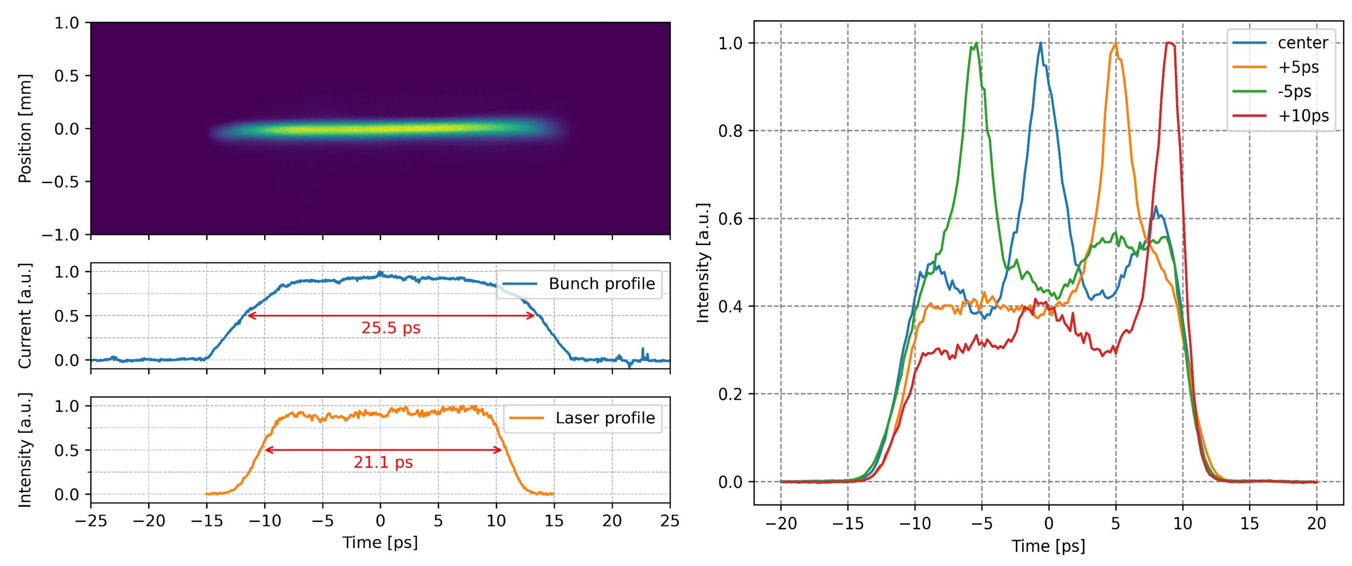
SLM Modeling and Pulse Shaping Simulations

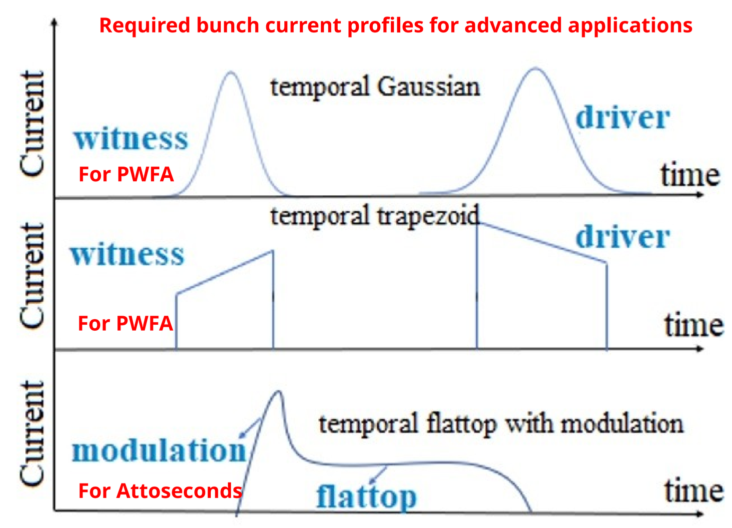
Simulate system non-linearities to generate data for ML inverse modeling to predict UV pulse shapes



UV Pulse Shaping & Advanced Applications

Demonstration of flattop laser and bunch profie shaping with high flexibility for advanced applications (e.g. attoseconds pulse generation, PWFA)





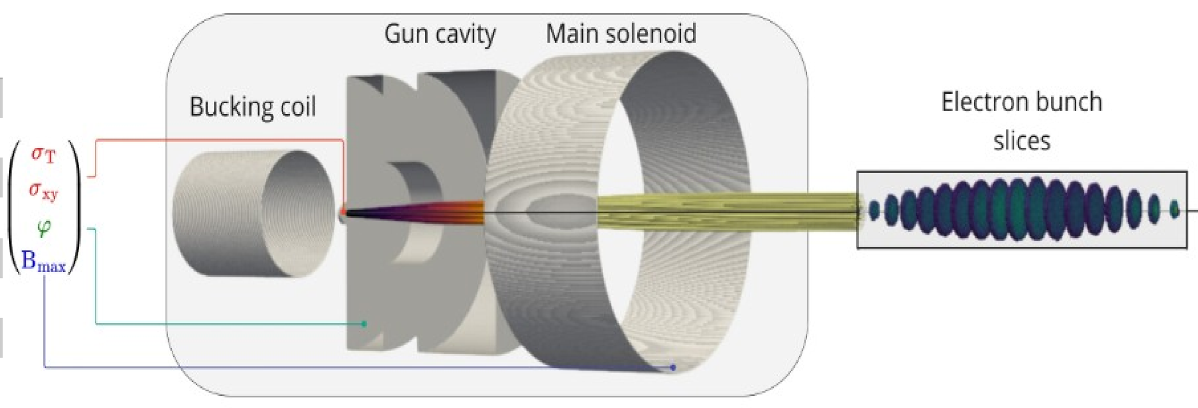
Successful Inverse Modeling & Reconstruction of Electron Bunch Slice Emittance – by A. Klemps

Photoinjector Digital Twin Modeling and Sampling

Development of end-to-end simulation, covering laser system and injector components

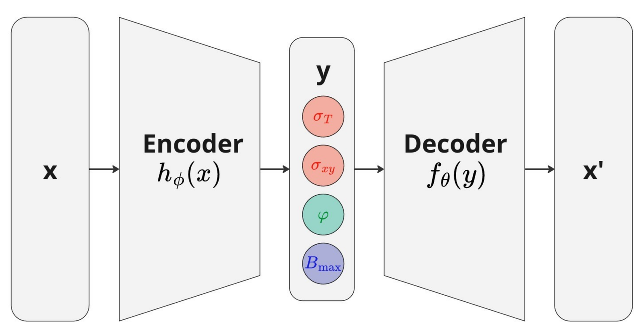
Modeling of the EuXFEL electron gun and sampling of 40.000 simulations with varying parameters using ASTRA embedded in self developed API interface.

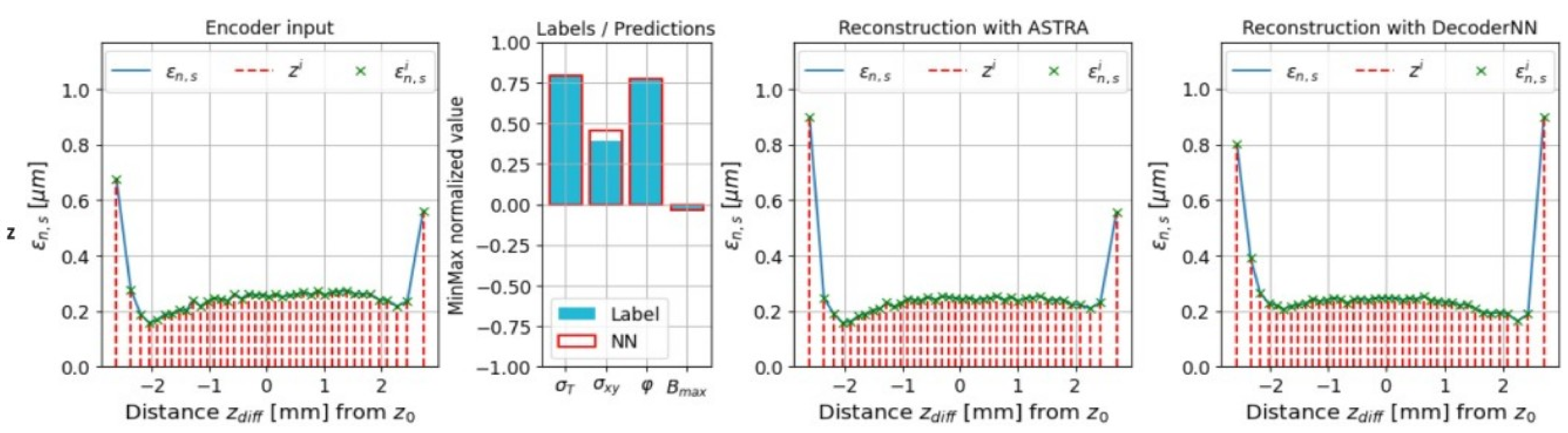
Parameter	Value/Range
Pulse length (FWHM)	5 to 15 ps
Spot size (RMS)	0.18 to 0.30 mm
Gun phase	-10 to 10 deg
Gun solenoid strength	0.15 to 0.3 T
Temporal pulse shape	Flattop
Transverse laser profile	Radial uniform
Gun gradient	57.6 MV/m
Bunch charge	250 pC



Evaluation of AutoEncoder Model

Parameter prediction & emittance reconstruction with inverse modeling via an Encoder-Decoder approach

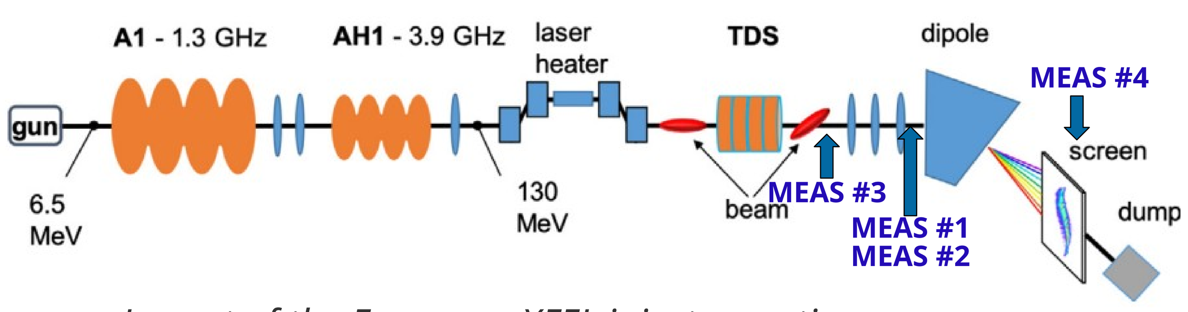




Excellent Results Obtained in End-to-End Optimization of Photoinjector Performance – by M. Cai

Experiments

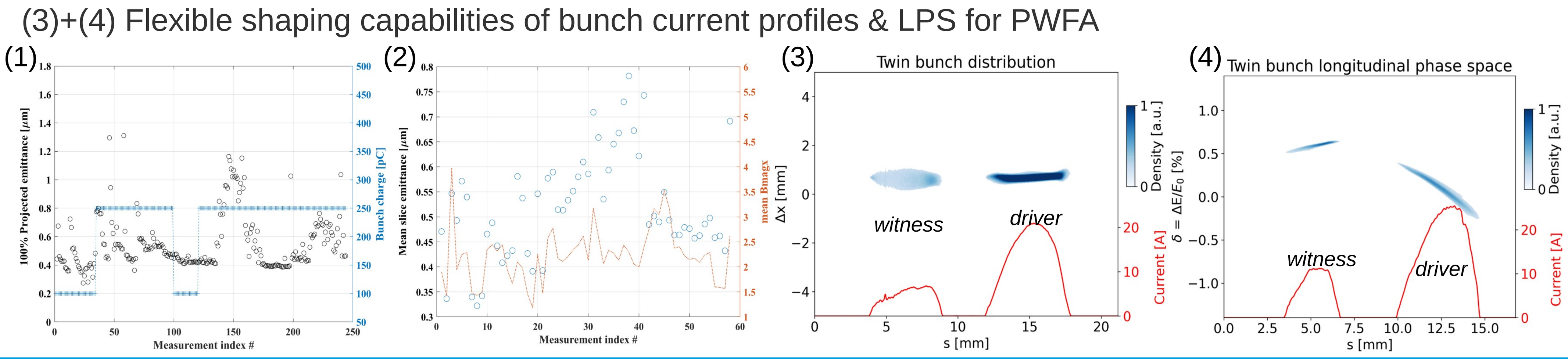
- Optimizing injector for HDC/CW & advanced applications (e.g. Plasma Wake-Field Acceleration, PWFA)
- Transfer study results to realistic photoinjector performance under operational machine conditions (1)-(4)



Layout of the European XFEL injector section

Measurement Results

(1) Projected emittance: 0.27 µm at 100 pC for HDC/CW (best ever), 0.41 µm at 250 pC for present XFEL
(2) Sliced emittance: 0.32 µm at 250 pC for present XFEL (best ever)
(3)+(4) Flexible shaping capabilities of bunch current profiles & LPS for PWFA



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