Virtual diagnostics for X-ray pulse characterization

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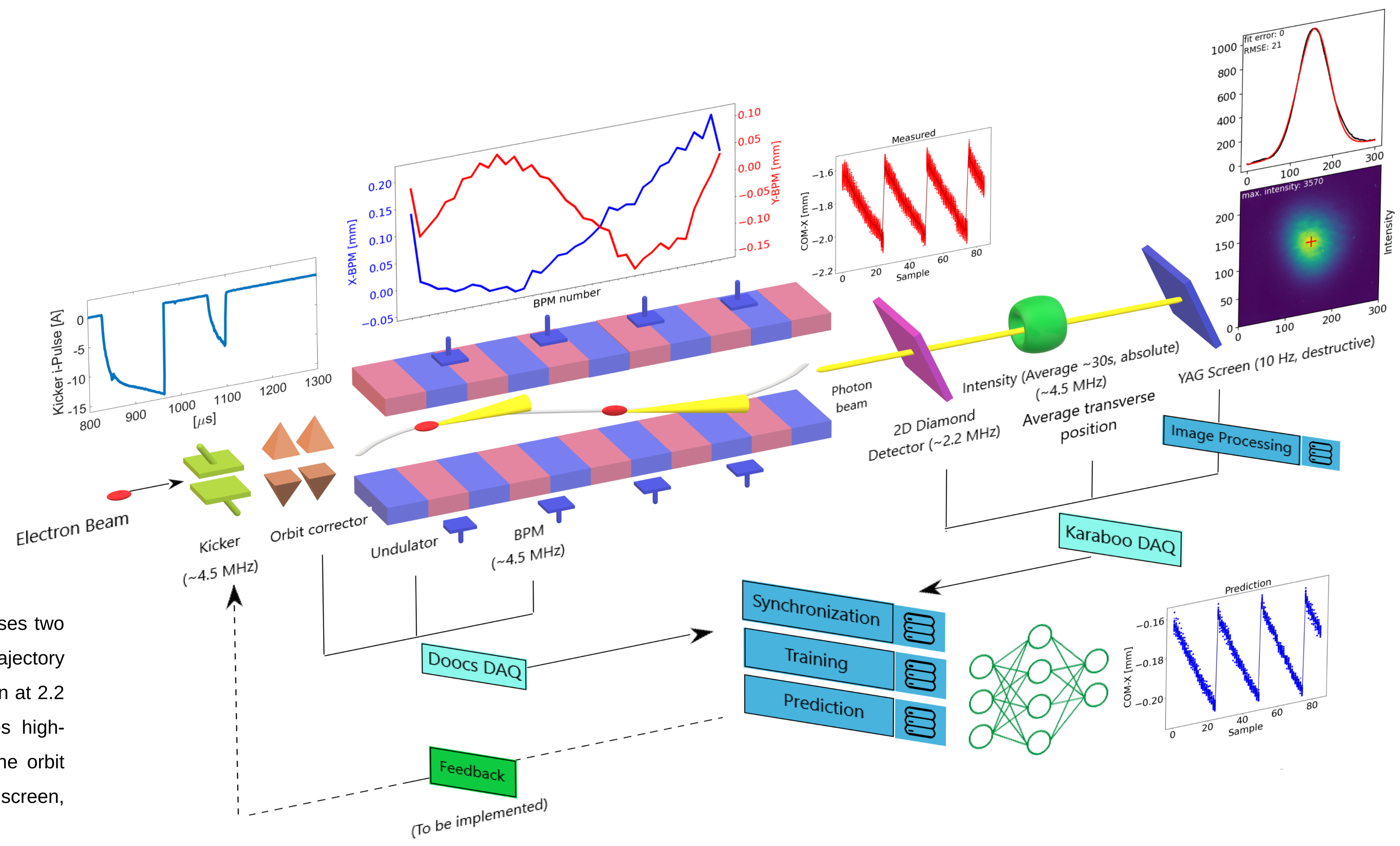
Introduction

Free-electron lasers (FELs) are advanced light sources capable of producing highly brilliant short pulses by using ultra-relativistic electron beams. They are crucial tools to drive novel photon science in various fields, from attosecond science to achieving high transverse and longitudinal coherence. Precise measurement and control of the electron beam properties both during acceleration and transport are crucial under nominal conditions, even more so for challenging FEL operation modes, which negatively affect stability. The extremely complex setups and beam-related instability of the FEL render both the stability and reproducibility of each shot an open challenge. Exemplary of this is the pointing jitter of the x-ray pulses. The two major sources of pointing instabilities are orbit jitter (MHz range) of the electrons entering the undulator and x-ray mirror vibrations (kHz range). This pointing instabilities lead to an additional effective intensity jitter at the interaction point. Furthermore, this could lead to damage to the sample, its holder, or any other beamline equipment. This work describes a way to predict the pointing of each photon pulse and shows supporting measurements up-to MHz intra-train repetition rate.

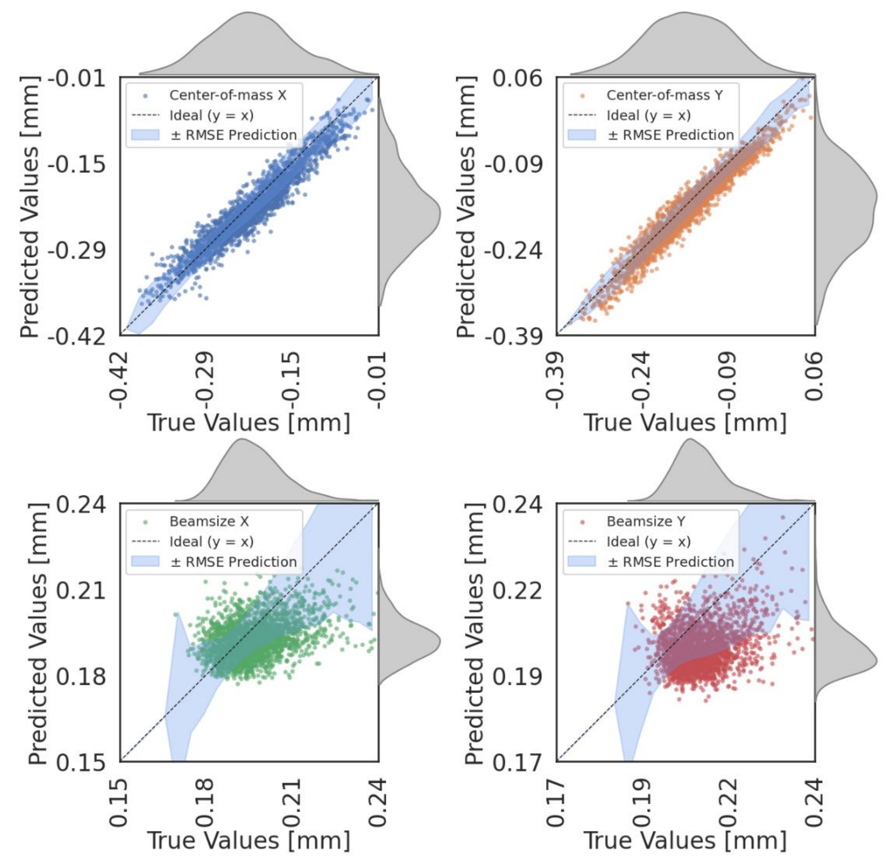
Photon Pointing Prediction Framework

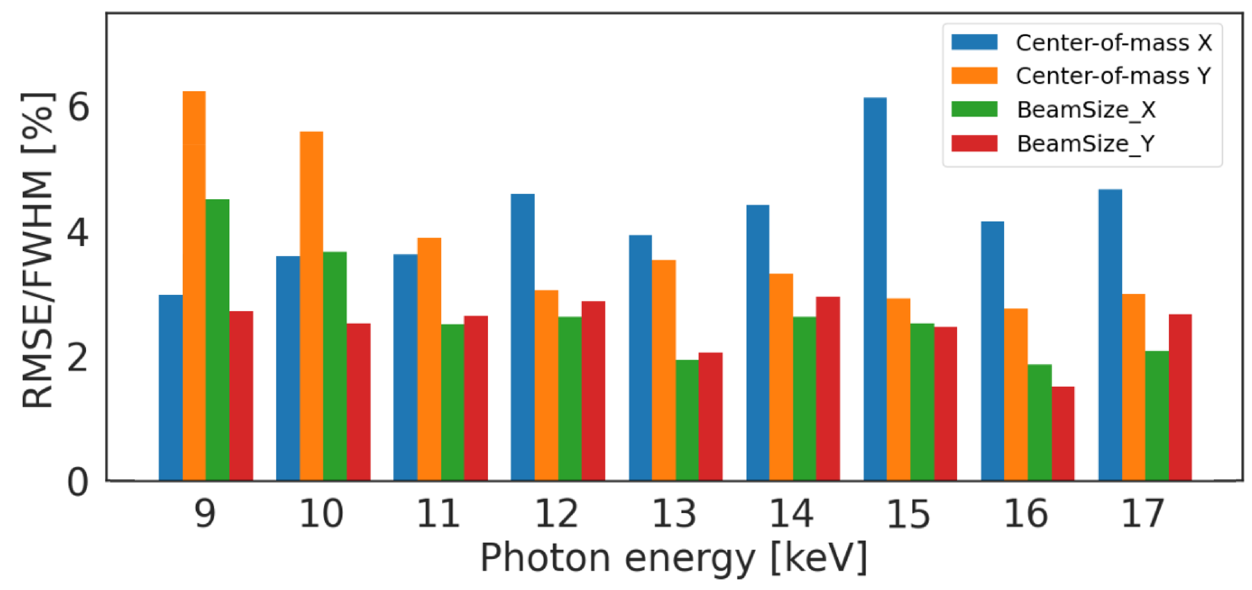


Real-time approach includes training and putting models in operation. The experimental setup uses two time scales for beam monitoring during training and validation. BPMs track the electron beam trajectory between bunch trains, while a 2D diamond detector measures the beam position within each train at 2.2 MHz. XGMs capture intensity and beam position, and a YAG screen (FEL imager) provides high-resolution beam imaging. The training process involves systematically varying the offsets of the orbit corrector to create various beam conditions. Synchronized data from BPMs, XGMs, and YAG screen, collected using control system, are used to train and validate the neural network model.

Prediction (Single Pulse)

Comparison of predicted versus true photon beam parameters at 13 keV. The top row shows the prediction performance for the photon beam center-of-mass in the horizontal (X, left) and vertical (Y, right) directions. The bottom row displays the predicted versus true values for the horizontal (X, left) and vertical (Y, right) beam sizes. The dashed line represents the ideal agreement (y = x), while the shaded blue region indicates the ±1 RMSE prediction interval. Marginal histograms illustrate the distribution of predicted and true values. The model demonstrates excellent agreement for center-of-mass predictions, with deviations primarily within the RMSE bounds. Beam size predictions show increased scatter, reflecting the greater complexity and variability in learning second-moment beam parameters from upstream diagnostics.

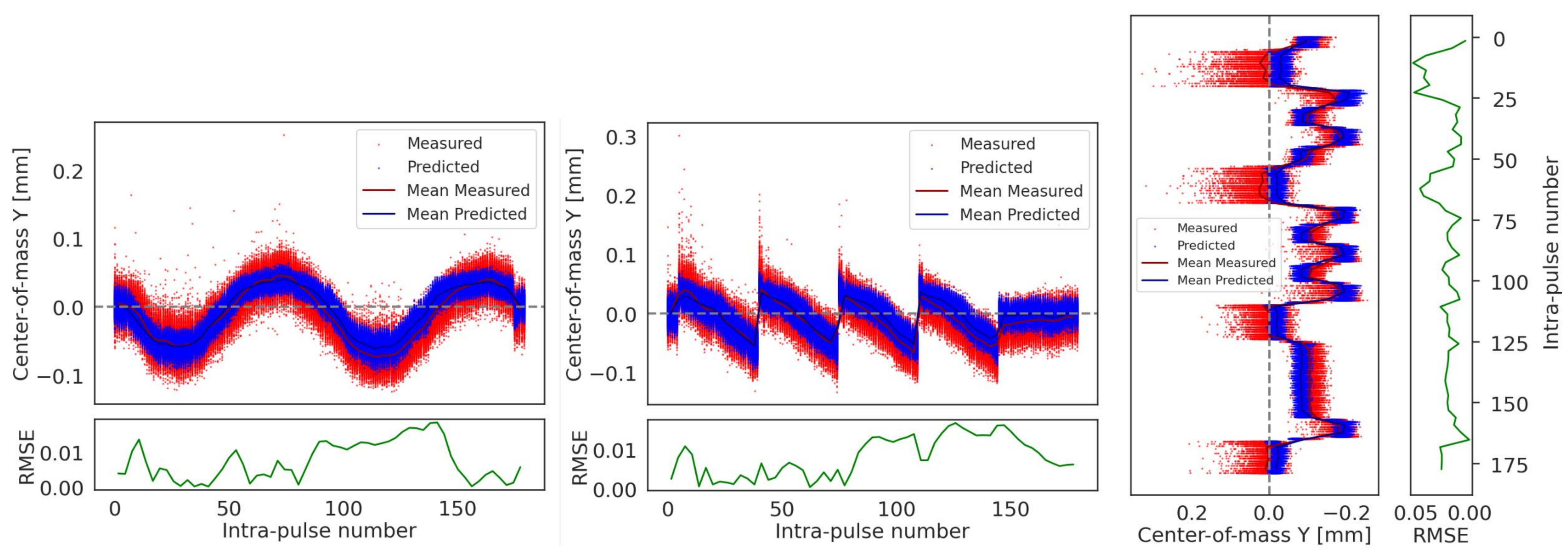




Root-mean-square error of the predicted photon beam properties normalized by the average FWHM of the photon beam size across various photon energies, with each energy serving as the test set while others are used for training.

Prediction (Many Pulses)

Intra-pulse prediction performance of the trained neural network for photon beam COM-Y at 17 keV comparing with measurements from a diamond sensor. Each panel compares measured (red) and predicted (blue) COM-Y positions over 180 intra-pulse bunches. The plots represent three distinct pulse patterns: a sinusoidal modulation (left), a step-like profile (middle) and FEL shape (right). Solid lines indicate the mean measured and predicted COM-Y per bunch number. The corresponding RMSE per bunch is shown below each plot, indicating high prediction accuracy across the full pulse train.



Conclusion

By leveraging readily available data from BPMs, our ANN model accurately predicts photon properties such as center-of-mass and beam size. The prediction model proved highly reliable across multiple photon energies, ensuring its robustness and versatility in varying operational conditions. The integration of high-frequency diagnostics with advanced data processing and predictive algorithms offers a non-invasive approach to overcome limitations associated with conventional diagnostics providing continuous monitoring and predictive insights into FEL performance at European XFEL. Our approach enables operators to make informed decisions in real time, optimizing beam trajectories, and enhancing the efficiency of photon pulse generation without interrupting operations. Future implementation of a feedback loop will close the control cycle, allowing for dynamic adjustments to the electron beam based on real-time diagnostics. The results suggest that integrating this predictive model into an active feedback system could pave the way for continuous, real-time beam corrections.

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