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MACHINE LEARNING-BASED RECONSTRUCTION OF ELECTRON RADIATION SPECTRA

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Abstract

The photon flux resulting from the interaction of a high-energy electron beam with a target, such as in the upcoming FACET-II experiments at SLAC National Accelerator Laboratory, can provide valuable information about the underlying dynamics of the electron beam at the interaction point. This project utilizes data from simulated plasma wakefield acceleration-derived betatron radiation experiments and high-field laser-electron-based radiation production to determine which methods can reliably reconstruct the key properties of the electron beam. The data from these two cases provide a wide range of photon energies, which increases confidence in the analysis methods. This work aims to compare several reconstruction methods and determine which one best predicts the original energy distributions based on simulated spectra. By analyzing the spectral and angular characteristics of the photon flux, valuable insights can be gained into the dynamics of the electron beam during the interaction process.

INTRODUCTION

Betatron radiation is a phenomenon that occurs when a relativistic electron beam undergoes transverse oscillations due to the presence of strong focusing fields. These oscillations result in the emission of electromagnetic radiation. In the case of betatron radiation, the focusing fields are due to a nominally uniform ion channel formed in a blowout regime of plasma wakefield acceleration (PWFA). Synchrotron radiation refers to the electromagnetic radiation produced by the transverse acceleration of very energetic charged particles. However, in specific cases encountered in modern applications, such as those found in advanced accelerator research, the radiation is more specifically referred to by the type of external force giving rise to the relevant acceleration. Betatron radiation and nonlinear inverse Compton scattering (NICS) are two such processes of high importance in advanced accelerator experimentation. Betatron radiation occurs when a beam of electrons undergoes harmonic transverse betatron oscillations due to a linear focusing force in plasma. The radiation produced from these oscillations provides information about the properties of the beam, such as emittance and energy, and can be used to reconstruct the transverse profile of the accelerated electron beam through statistical techniques such as Maximum Likelihood Estimation (MLE).

Beam-plasma interactions can result in the emission of gamma rays, which exhibit distinct experimental signatures that provide insights into the physics of interactions at ultra-short spatial and temporal scales. Betatron radiation serves as a valuable probe for studying high-energy beam-plasma and beam-radiation interactions, and understanding these interactions is essential for the advancement of modern accelerator techniques, as discussed in recent studies [1, 2].

ANALYSIS

In PWFA, a highly intense laser pulse is utilized to generate a plasma wake in a plasma medium. The electron beam is then injected into this wake, where it experiences a strong focusing force due to the density gradient in the plasma. The focusing force causes the electron beam to undergo transverse oscillations, resulting in the emission of betatron radiation. The wavelength of the betatron radiation is determined by the period of the transverse oscillations of the electron beam, which depends on the strength of the focusing fields and the initial transverse displacement of the electron beam.

Machine learning methods have been explored for gamma spectroscopy and imaging in the context of PWFA. For instance, a neural network approach has been used to classify gamma-ray spectra based on their energy and source. Another study utilized convolutional neural networks to reconstruct the distribution of gamma-ray emitting sources from measurements made by an array of detectors. These machine learning methods have the potential to significantly enhance the speed and accuracy of gamma-ray spectroscopy and imaging, which can be particularly valuable in high-energy physics experiments as shown in Fig. 1.

The process of computing a radiation spectrum involves using a grid of values for ϕ_x, ϕ_y, and ϵ, and integrating over $d\Omega = d\phi_x d\phi_y$. Due to the independent evaluations of radiation intensity spectrum contributions, parallelization techniques can be utilized to speed up the computation. In the task of identifying a beam's spot size using maximum likelihood estimation (MLE), radiation spectra from several beams with different spot sizes are obtained using a custom tracking code in Fig. 2. A known test spot size is then chosen, and an additional radiation spectrum is obtained for that beam. The MLE technique is used to find the best match between the observed radiation spectrum and the predicted spectrum based on the test spot size. By repeating

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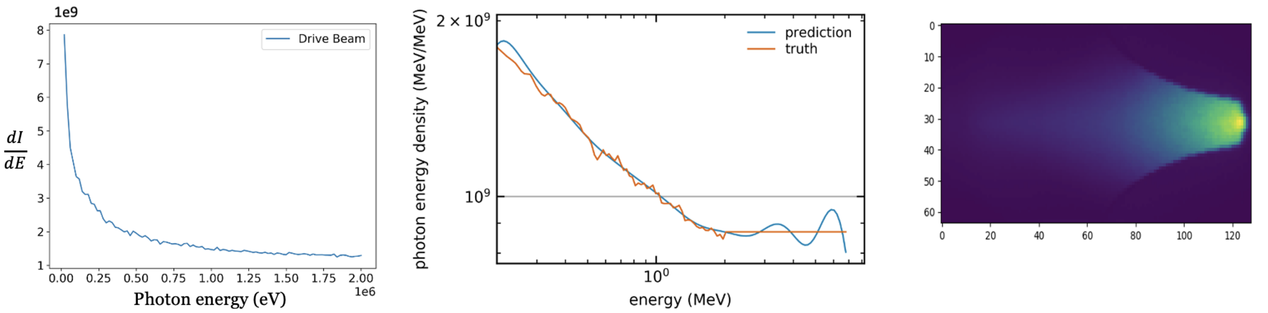

Figure 1: Left: Betatron radiation spectrum is plotted for E310 parameters using QuickPIC code. Middle: Compared the truth and prediction of spectrum using EM algorithm. Right: Betatron radiation spectrum using Geant 4 on y (mm) and z (mm) scintillator screen.

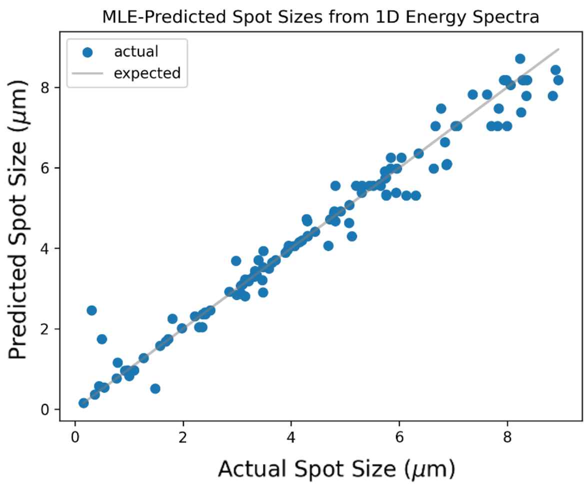

Figure 2: Overall spot size prediction results of the MLE algorithm used with 310 sets of reference data and 120 test cases in the form of 1D radiation spectra. The MSE for these predictions is 0.186 μm^2.

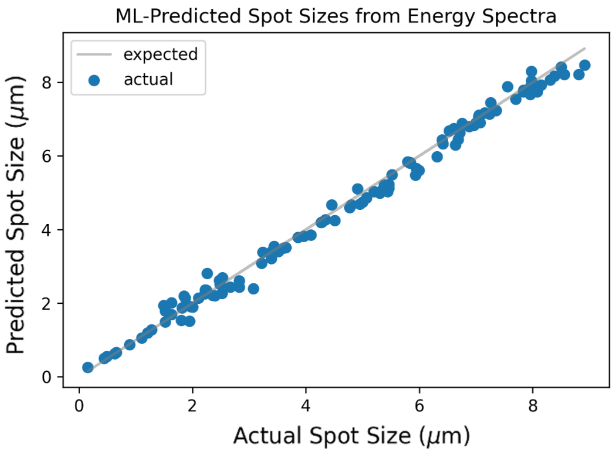

Figure 3: ML model predictions of spot size using 1D radiation spectra normalized according to their K value. The MSE is 0.0513 μm^2, and the inaccuracies at low spot sizes are no longer present.

this process for various test spot sizes, the spot size of the original beam can be determined.

The chosen neural networks utilize Rectified Linear Unit (ReLU) activation functions, which set all negative values to zero and return the input value for positive values. ReLU is a popular activation function in neural networks due to its computational efficiency and faster convergence during training. The Adam optimizer is a widely used gradient-based optimization algorithm for training neural networks as shown in Fig. 3. It adapts the learning rate for each weight during training, leading to faster convergence and improved results. Mean Squared Error, is a commonly used loss function in regression problems. It calculates the average of the squared differences between the predicted and actual values. During training, the neural network aims to minimize this loss function to improve its performance on the task.

The process of generating training data involves creating an energy distribution and multiplying it by a matrix to generate the corresponding radiation spectrum (or ”y”-vector) that would be measured by PEDRO. To simulate real-world noise from scattered electrons during the pair production process, low-level noise vectors are added to the ”y”-vectors.

MLE is an iterative algorithm that converges to the solution that is most probable given an initial guess for the solution of an equation. In the current context, MLE is used to estimate a series of parameters from the output of PEDRO in order to calculate the original energy distribution. This method converts the problem of calculating the energy distribution from an analytical problem to a statistical one. The process of minimizing the function $f(x)$ using the least-squares optimization algorithm is employed to find the most likely energy distribution. To determine whether the function is strongly convex and has a unique global minimum, the values of the matrix $\hat{S}$ must be taken into account. The results of the quantum electrodynamics test case show that all three methods used (QR decomposition, MLE, and ML-MLE hybrid) provide similar performance levels. The QR decomposition method requires the least amount of computational time to implement due to its non-iterative algorithm in conjunction with least squares optimization. The ML and

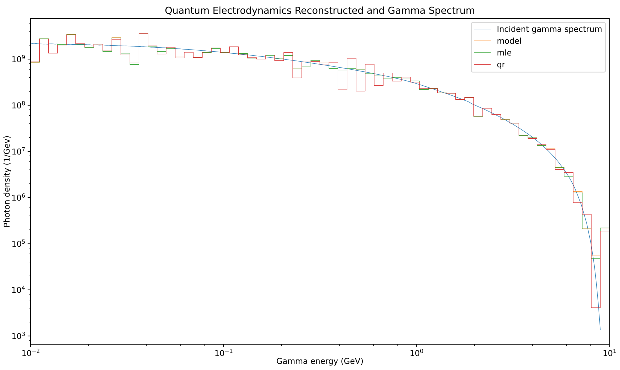

Figure 4: Reconstruction of quantum electrodynamics case using three different methods.

ML-MLE hybrid approaches provide highly similar performance levels, with the hybrid approach providing somewhat smoother solutions. Figure 4 displays the results obtained from all three methods used in the quantum electrodynamics test case.

QR decomposition is a numerical linear algebra technique that decomposes a matrix into an orthogonal matrix Q and an upper triangular matrix R. The QR decomposition method is commonly used to solve linear least-squares problems, which involve finding the solution to a system of equations with more unknowns than equations. The advantage of using the QR decomposition method is that it is numerically stable and can be applied to solve a wide range of linear least-squares problems. Additionally, the QR decomposition method is computationally efficient, making it well-suited for large-scale problems.

CONCLUSION

Betatron radiation and related processes are essential tools for studying high-energy beam-plasma and beam-radiation interactions. MLE and machine learning methods are becoming increasingly important for extracting valuable information about beam parameters from radiation measurements, which can provide insights into beam dynamics and improve the performance of particle accelerators.

The development of new PWFA facilities, such as FACET-II, FLASHForward, and EuPRAXIA, is providing exciting new opportunities to explore the physics of high-gradient acceleration and related phenomena. These facilities offer advanced capabilities for producing and manipulating high-energy beams, generating strong fields, and probing the dynamics of charged particles. The use of advanced measurement techniques, combined with MLE and machine learning methods, can help unlock the full potential of these facilities and drive new discoveries in high-energy physics. Overall, the combination of betatron radiation, MLE, and machine learning techniques provides a powerful toolkit for studying beam-plasma and beam-radiation interactions and advancing the field of particle acceleration. With continued advancements in accelerator technology and data analysis methods, we can expect to see exciting new discoveries and applications in the coming years.

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