PROCEEDINGS OF SCIENCE

Quantum algorithms for charged particle track reconstruction in the LUXE experiment

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LUXE (Laser Und XFEL Experiment) is a new experiment in planning in Hamburg, which will study Quantum Electrodynamics at the strong-field frontier. LUXE intends to measure the positron production rate in this unprecedented regime by using, among others, a silicon tracking detector. The large number of expected positrons traversing the sensitive detector layers results in an extremely challenging combinatorial problem, which can become computationally expensive for classical computers. We investigate the potential future use of gate-based quantum computers for pattern recognition in track reconstruction, based on a quadratic unconstrained binary optimisation and a quantum graph neural network. This report introduces these approaches and compares their performance with a classical track reconstruction algorithm.

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1. Introduction

LUXE (Laser und XFEL experiment) [1] is a proposed experiment at DESY and European XFEL to study strong-field Quantum Electrodynamics (QED) in electron-laser and photon-laser collisions using the high energy XFEL electron beam and a high power laser. The photon-laser collision is achieved by converting the electron beam to a photon beam via Bremsstrahlung with a target.

The two processes of interest at LUXE are the non-linear Compton scattering process of a photon radiated from an electron in the laser field,

$$e^- + n\gamma_L \rightarrow e^- + \gamma, \tag{1}$$

where n is the number of laser photons γ_L participating in the process and the non-linear Breit-Wheeler pair creation,

$$\gamma + n\gamma_L \rightarrow e^+ + e^-, \tag{2}$$

from the interaction of a photon in the laser field, where the photon can be the Compton photon from the first process in the electron-laser collisions.

LUXE aims to make precise measurements of these interactions in a transition from the perturbative to the non-perturbative regime. One of the parameters that characterise this is the field intensity parameter ξ also known as the charge-field coupling, defined as

$$\xi = \frac{m_e E_L}{\omega_L E_{cr}}, \tag{3}$$

where m_e is the electron mass, E_L is the laser field strength, ω_L is the frequency of the laser and E_{cr} is the critical field strength, also known as the Schwinger limit defined as $E_{cr} = m_e^2 c^3/e\hbar$.

The Breit-Wheeler pair production rate as a function of the ξ is a key measurement in the experiment. This is achieved by measuring the positron rate using a four-layered silicon pixel tracker placed after a dipole magnet which directs the positrons to the tracker and separates them from the electrons, as shown in Figure 1.

Figure 2 shows the expected number of positrons per bunch crossing as a function of ξ for electron-laser and photon-laser mode in LUXE phase-0 (40 TW laser) and phase-1 (350 TW laser). Due to the high track multiplicities and occupancies expected at LUXE, tracking becomes very challenging. The potential use of gate-based quantum computers for pattern recognition in track reconstruction was thus investigated in Ref. [2] and summarised here.

2. Methods

Simulated events from the signal interactions propagated through the dipole magnet and tracking detector are used in this study. The setup assumes a laser power of 40 TW and ξ values ranging from 3 to 7, corresponding to numbers of positrons between 100 and 70,000. The starting point for the pattern recognition is either doublets or triplets, defined as a set of two or three hits in consecutive detector layers. An angle-based pre-selection is applied on the initial doublet or triplet candidates to reduce the combinatorial candidates while being close to fully efficient for signal.

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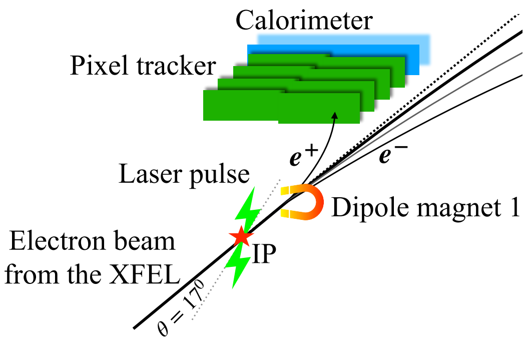

Figure 1: Layout of the LUXE experimental setup in the positron detection system in the electron-laser running mode. Reproduced from Ref. [2].

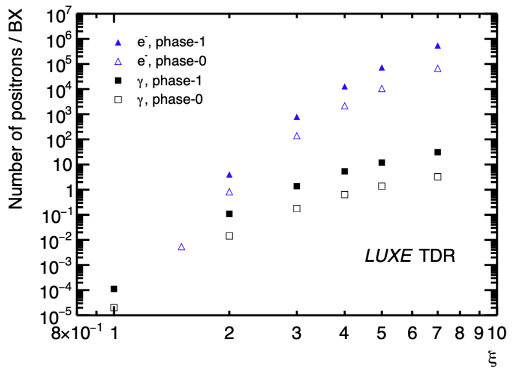

Figure 2: Number of positrons produced per bunch crossing as a function of the field intensity parameter ξ for electron-laser and photon-laser mode in LUXE phase-0 and phase-1. Reproduced from Ref. [1].

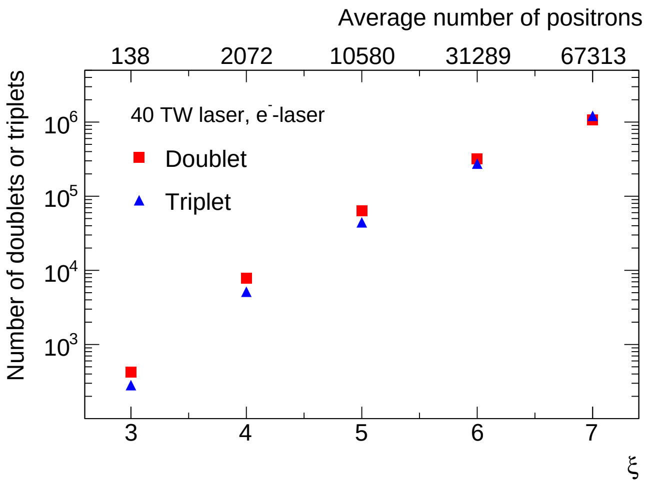

Figure 3: Number of pre-selected doublets and triplets as a function of ξ being studied. Reproduced from Ref. [2].

Figure 3 shows the number of doublets and triplets passing the pre-selection criteria as a function of ξ.

Three methods for track finding are tested and compared. The quantum graph neural network (QGNN) and the quadratic unconstrained binary optimisation (QUBO) are both hybrid quantum-classical approaches which treat the tracking problem as a classification task and optimise globally to find the best track candidates. These two are compared to a classical benchmark using a combinatorial Kalman filter (CKF) [3, 4] which is a local seeded track-finding method.

2.1 Quantum graph neural network

This method is based on a graph neural network that consists of both classical neural network layers and quantum circuits, as implemented in Ref. [5]. The graph is constructed from doublets, where the hits are nodes and the connections between hits are edges. All nodes of consecutive layers are connected and only the ones that satisfy the pre-selection criteria are kept. Alternating EdgeNetwork and NodeNetwork are applied in the model, such that the model adaptively learns with each iteration which hit connections are important. EdgeNetwork is applied finally to obtain the predictions for the edge connections and the edge/doublet with scores above a chosen threshold are retained to form track candidates.

2.2 Quadratic unconstrained binary optimisation

The QUBO method classifies triplets that can form the best track candidates by minimising the objective function

$$O = \sum_{i}^{N} \sum_{j<i} b_{ij} T_i T_j + \sum_{i=1}^{N} a_i T_i, \tag{4}$$

where T_i and T_j are the selection state of the triplets, $T_i, T_j \in \{0, 1\}$, and a_i and b_{ij} are coefficients that quantify the quality of the individual triplets and the compatibility between triplet pairs, respectively. The coefficient b_{ij} is defined such that it is negative for compatible triplet pairs and penalises triplets that are in conflict. In this way, the solution which results in the minimum of the QUBO yields the optimal set of triplets. The QUBO can be mapped to an Ising Hamiltonian and its minimisation is equivalent to finding the ground state of the Hamiltonian. The variational quantum eigensolver (VQE) [6], a hybrid quantum-classical algorithm, is used to find the ground state, using a simulation of quantum circuits. The exact solution using matrix diagonalisation of the QUBO is used as a benchmark.

2.3 Combinatorial Kalman filter

In the classical CKF technique, track finding starts from seeds, which are the triplets formed from the first three detector layers. An initial estimate of track parameters is obtained from the seed and is used to predict the next hit and is updated progressively, with the measurement search performed at the same time as the fit.

3. Results

Track candidates are formed by combining the selected doublets (with the QGNN approach) or triplets (with the QUBO approach) into quadruplets or found directly with the CKF method. They are required to have four hits, fitted and further processed via an ambiguity-solving procedure which removes worse quality track candidates that share hits, based on the χ^2/ndf of the track fit. The procedure allows no more than one shared hit per track.

The performance of the various tracking methods is assessed using the track reconstruction efficiency and fake rate as metrics, defined as

$$\text{Efficiency} = \frac{N_{\text{tracks}}^{\text{matched}}}{N_{\text{tracks}}^{\text{generated}}} \quad \text{and} \quad \text{Fake rate} = \frac{N_{\text{tracks}}^{\text{fake}}}{N_{\text{tracks}}^{\text{reconstructed}}}\,. \tag{5}$$

A track is considered matched if at least three out of four hits are matched to the same particle.

Figure 4 shows the efficiency and fake rate as a function of ξ for the tested methods, averaged over ten bunch crossings. The results for the QGNN-based tracking are shown up to $\xi = 4$ and VQE up to $\xi = 6$ due to prohibitive computational cost. All methods show comparable performance. The QUBO approach has a slightly higher efficiency than the CKF technique but at the expense of a higher fake rate. The QGNN method relies on sufficient training statistics which is not supplied by the chosen 90 bunch crossings of the training dataset at $\xi = 3$ due to the low number of particles. By increasing the statistics of the training data, the expected efficiency is recovered.

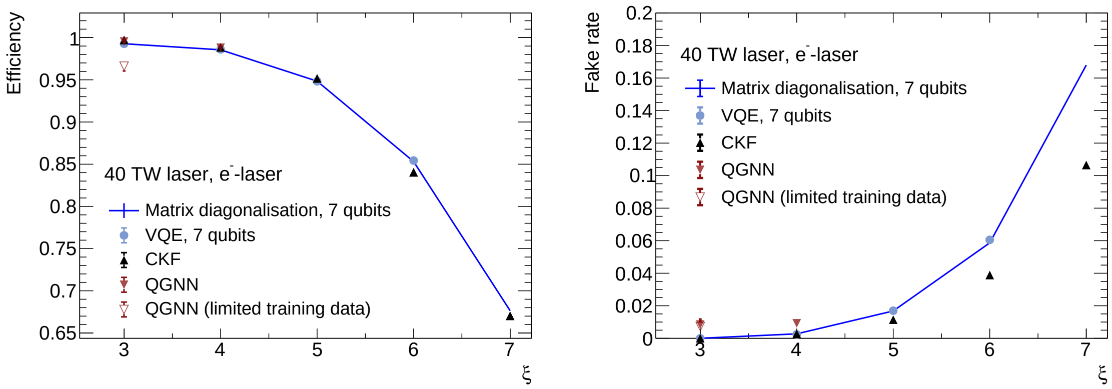

Figure 4: Track reconstruction efficiency and track fake rate as a function of ξ. Reproduced from Ref. [2].

The track reconstruction efficiency and fake rate as a function of the positron energy for $\xi = 5$ are shown in Figure 5 for the CKF and QUBO tracking methods. The behaviour is similar for the two methods with CKF having a lower fake rate. The performance deteriorates at moderate energy which corresponds to the highest detector occupancy where particles are very close to one another. The reduced efficiency of QUBO at low energy is due to the loss in efficiency during the pre-selection of the triplets due to higher scattering.

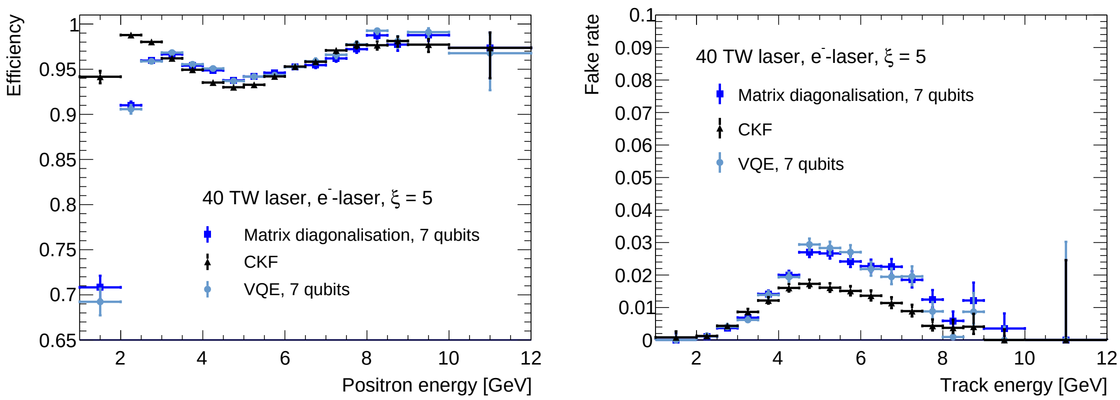

Figure 5: Track reconstruction efficiency and track fake rate as a function of energy for $\xi = 5$. Reproduced from Ref. [2].

4. Summary

The use of hybrid quantum-classical algorithms in a QUBO formulation and QGNN for tracking was investigated and similar performance as the best classical method was achieved. In the future, we aim to perform a systematic study of these algorithms using noisy intermediate-scale quantum devices, study even more extreme environments and explore regions where quantum computing could outperform traditional methods.

References

[1] H. Abramowicz *et al.*, *Technical Design Report for the LUXE Experiment*, [2308.00515].

[2] A. Crippa *et al.*, *Quantum algorithms for charged particle track reconstruction in the LUXE experiment*, [2304.01690].

[3] R. E. Kalman, *A New Approach to Linear Filtering and Prediction Problems*, *J. Basic Eng. 82, 1 (1960)*.

[4] P. Billoir, *Track Fitting With Multiple Scattering: A New Method*, *Nucl. Instrum. Meth. A 225 (1984)*.

[5] C. Tüysüz *et al.*, *Hybrid quantum classical graph neural networks for particle track reconstruction*, *Quantum Machine Intelligence 3 (2021) 2, 29*, [2109.12636].

[6] A. Peruzzo *et al.*, *A variational eigenvalue solver on a photonic quantum processor*, *Nat. Commun. 5, 4213 (2014)*.