PROCEEDINGS OF SCIENCE

Assessing the potential of quantum annealers for track reconstruction at LUXE

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LUXE (Laser Und XFEL Experiment) is a proposed DESY experiment using the European XFEL electron beam and a high-intensity laser. The experiment's primary aim is to investigate the transition from the well-probed perturbative to the non-perturbative Quantum Electrodynamics regime. In LUXE, positrons are generated and directed towards a four-layered silicon pixel detector, with occupancies of up to 100 hits/mm^2 for the initial phase. Reconstructing tracks from a substantial set of hits poses a significant challenge for classical computers. To address this challenge, the novel approach based on formulating the track pattern recognition task as a quadratic unconstrained binary optimisation (QUBO) problem is adopted. Classically, the expected performance of a quantum annealer for QUBO problems can be studied using Simulated Annealing. In this report, the performance of reconstructing tracks from LUXE using Simulated Annealing is benchmarked against results from a gate-based quantum computing simulator, as well as against the classical method of employing a Combinatorial Kalman Filter.

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1. Introduction

LUXE (Laser- und XFEL Experiment) is a proposed experiment that aims to investigate the transition from the perturbative to the non-perturbative regime of quantum electrodynamics (QED). This will be achieved by using high-power lasers and an electron beam provided by the Eu.XFEL to measure interactions of real photons with electrons and photons at field strengths where the coupling to the electric charge becomes non-perturbative [1]. The experiment will reach field strengths that exceed the Schwinger limit at the rest frame of the probe,

$$E_{\text{crit}} = \frac{m_e^2 c^3}{e} = 1.32 \times 10^{18}\,\text{V}\,\text{m}^{-1}, \tag{1}$$

at which non-linear effects become significant. Strong-field QED is dependent on the dimensionless laser intensity parameter ξ that can be defined using

$$\xi = \frac{m_e c^2}{\hbar\omega_L}\frac{E_L}{E_{\text{crit}}}, \tag{2}$$

which gives a measure of the number of laser photons interacting with the electron at a given time. Here, E_L is the laser field strength and ω_L is the laser frequency. In LUXE, single electrons from the Eu.XFEL interact with n optical photons γ_L and create a high-energy Compton photon γ via the non-linear Compton process, $n\gamma_L + e \rightarrow \gamma + e$. In the alternative γ-laser-mode, a converter target is placed into the electron beam path to produce a high-energy photon beam via Bremsstrahlung. Subsequently, the non-linear Breit-Wheeler process is enabled for both set-ups, where a real high-energy photon absorbs multiple laser photons to produce a physical electron-positron pair, $n\gamma_L + \gamma \rightarrow e^+ + e^-$.

The transition from the perturbative to the non-perturbative regime in LUXE is characterised by (1) a shift in Compton edge and (2) a deviation from the power law in the positron-electron production rate. Accurate positron tracking is needed to investigate the latter effect with high precision. Positrons specifically are tracked utilising a four-layered Silicon pixel detector. In LUXE, the challenge for positron reconstruction from detector hits lies in the substantial range of produced positrons per bunch crossing and localised high occupancy regions for high ξ. The reconstruction of trajectories from a set of hits is a combinatorial problem challenging for a classical computer to solve, with a time complexity that scales exponentially with the number of hits. Even classical algorithms developed to address this challenge, such as the Combinatorial Kalman Filter, may not scale well for high particle multiplicities. Quantum computers, on the other hand, are anticipated to yield significant improvements in terms of computational speed for specific optimisation problems, enabling more rapid convergence to the optimal solution.

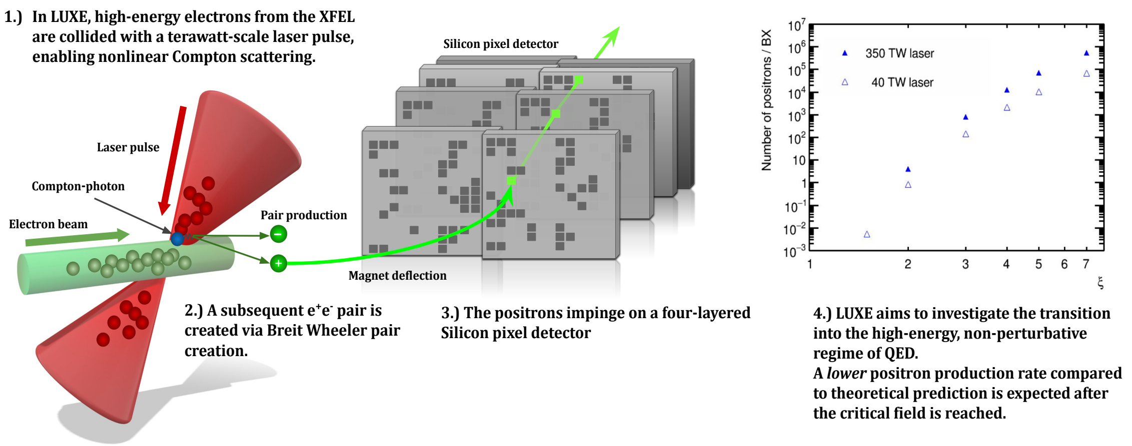

Figure 1: Schematic overview of positron tracking in LUXE.

2. Methods

All methods are based on an idealised setup where particle multiplicities and the detector geometry can be specified. The track reconstruction problem is formulated as a quadratic unconstrained binary optimisation (QUBO), a binary quadratic model closely connected to the Ising Model. The QUBO is expressed as

$$O(a;b;T) = \sum_{i=1}^{N} a_i T_{ii} + \sum_{i}^{N} \sum_{i<j}^{N} b_{ij} T_i T_j, \quad T \in \{0,1\}. \tag{3}$$

In quantum annealing, the a_i's act as bias weights in the form of a magnetic field, influencing the probability of a qubit collapsing to 0 ($a_i < 0$) or 1 ($a_i > 0$). The coupling strength b_{ij} influences two qubits in the form of couplers [2, 3]. To utilise the QUBO formulation, hits are grouped into triplets. A triplet $T^{a,b,c}$ consists of three hits a, b, c on subsequent planes under the constraint of classical pre-selection. The status of the triplets is encoded as a binary vector, a 1 corresponds to the triplet being kept, while a 0 means it is discarded. The individual coupling terms b_{ij} in equation 3 are chosen depending on the interaction the respective triplet pair (T_i, T_j) partakes in. We defined the weights a_i dependent on the angle inside the triplet T_i to populate the interval $[-1, 1]$. The coefficient b_{ij} is computed from the doublets forming the two considered triplets. If two triplets are of the form $T_i^{a,b,c}$ and $T_j^{b,c,d}$, it is taken to be the norm of the sum of the standard deviations of the doublet angles in the xy and yz planes, translated and scaled to populate the [-1, -0.9] range. If the two triplets are in conflict, meaning they do not form a track candidate but still share hits, the coefficient b_{ij} is set to one. For all other triplet pairs, b_{ij} is set to zero [4]. We utilize D-Wave's quantum annealing simulator, **neal** [5], to solve QUBOs for bunch crossings with complexity up to $\xi = 5$. In the initial phase of LUXE, this corresponds to an estimated count of 10^4 positrons. The results are compared to classical track reconstruction using a Combinatorial Kalman Filter and a gate-based quantum computing simulator combined with the Variational Quantum Eigensolver algorithm. For the latter, the QUBO has to be partitioned due to simulator requirements.

3. Results

Candidates for tracks are created by merging triplets to form quadruplets, or they are identified directly using the Combinatorial Kalman Filter (CKF) approach. These candidates must include four hits. They are further refined through a method that resolves ambiguities, where lower-quality track candidates that overlap in hits are eliminated, using χ^2/ndf. The process ensures that tracks do not share more than one hit. To evaluate the effectiveness of these different track detection methods, we use two key performance indicators

$$\text{Efficiency} = \frac{N^{\text{matched}}_{\text{tracks}}}{N^{\text{generated}}_{\text{tracks}}}, \quad \text{and} \quad \text{Fake rate} = \frac{N^{\text{fake}}_{\text{tracks}}}{N^{\text{reconstructed}}_{\text{tracks}}}. \tag{4}$$

Here, we define a matched track as having at least three same-particle hits. In figure 2, both efficiency and fake rate are plotted for all three methods as a function of ξ. Every technique displays comparable performance. The difference in fake rate for the gate-based method may arise from the required partitioning to considerably smaller problem sizes.

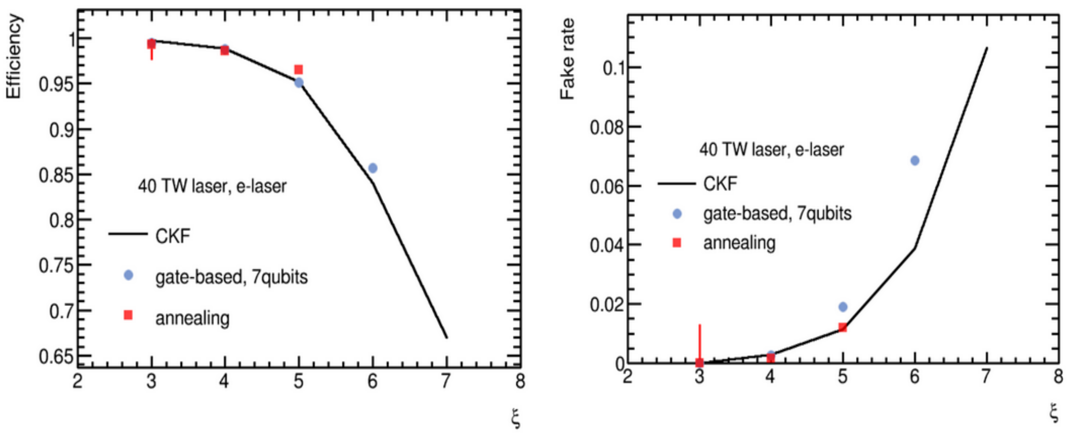

Figure 2: Efficiency and fake rate as a function of ξ for simulated annealing compared to track reconstruction using a Combinatorial Kalman Filter and a gate-based quantum computer with a QUBO partitioning size of 7.

4. Summary

We explored the application of the QUBO formulation in tracking tasks using simulated annealing and simulated gate-based quantum computers and found their performance to be on par with state-of-the-art classical approaches. Our goal is to conduct an extensive analysis of these algorithms on noisy intermediate-scale quantum (NISQ) devices.

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