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Track Reconstruction using Quantum Computing for LUXE

Abstract

LUXE (LASER Und XFEL Experiment) is a new planned experiment at DESY with the aim to study Quantum Electrodynamics (QED) in the strong-field in order to perform precision measurements to investigate the transition into the non-perturbative regime of QED. LUXE intends to measure the positron production rate in this regime using a silicon tracking detector, among a variety of other detectors. The large number of positrons traversing the detector per bunch crossing, with an upper limit of about 10^6, becomes an exceptionally hard combinatorial problem for classical computers. Pattern recognition plays a vital role in track reconstruction and my project explores the use of quantum computing to perform track reconstruction for a simple example in order to investigate the pattern finding performance of simulated devices and a real quantum device.

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1 LUXE

LUXE [1] will combine the high-quality and high-energy electron beam of the European XFEL (X-ray Free Electron Laser) with a powerful laser to explore the uncharted terrain of quantum electrodynamics characterised by both high energy and high intensity in the non-perturbative regime. The two processes of interest shown in Figure 1 [1] are non linear Compton scattering, where the photon is radiated from the electron in the laser field,

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

and the non-linear Breit-Wheeler pair creation, from the interaction of a photon (which may be from the Compton process) in the laser field.

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

Where n is the number of laser photons γ_L in the process.

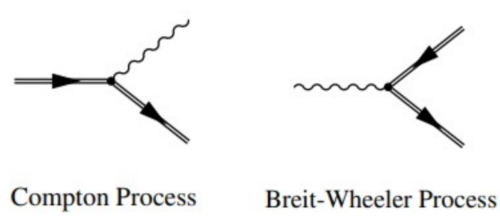

Figure 1: Feynman diagrams showing processes for the non linear Compton scattering and Breit-Wheeler pair production in the non-pertubative regime.

In the non-perturbative regime the Compton edge in the energy spectrum is shifted to higher energies, and it is predicted that the Breit-Wheeler pair production rate has a slower increase with increase in laser intensity than that of the perturbative regime. The laser field intensity ξ given bu equation 3 characterises these interactions and is defined as,

$$\xi = \sqrt{4\pi\alpha}\frac{\epsilon_L}{\omega_L m_e} = \frac{m_e \epsilon_L}{\omega_L \epsilon_{cr}} \tag{3}$$

where α is the fine structure constant, ϵ_L is the laser field strength, ω_L is the laser frequency, m_e is electron mass and ϵ_{cr} is the critical field strength also referred to as the Schwinger limit, a scale in

QED where above this limit the electromagnetic field is expected to become non-linear.

The experimental setup is shown in Figure 2 below, the electron beam is guided to the interaction point (IP), where it collides with the laser. The electrons and positrons produced in these interactions are then deflected and separated by a magnet and detected, the beam forward direction is in the z plane.

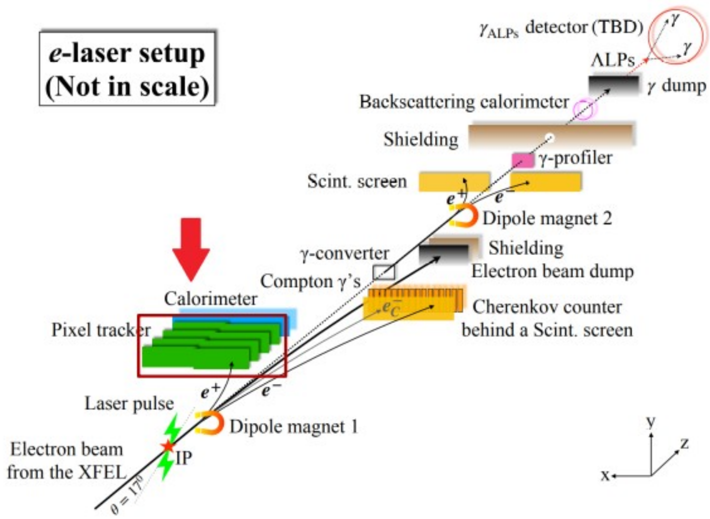

Figure 2: Schematic layout of LUXE for e-laser setup [1]

The tracking study presented concerns only positrons which are detected using the four layer silicon pixel tracking detector. Two main tracking challenges are to maintain good linearity as well as keep a low background rate per bunch. As well, there are up to one million positrons per bunch crossing which can be quite a demanding challenge for classical computers. To try and cope with this, the potential use of quantum computing is investigated.

2 Pre-Selection

The building blocks of track candidates are doublets and triplets, defined as a set of two or three hits on consecutive layers respectively. Doublets are formed first, in the detector area there is no magnetic field, but the tracks are bent initially by a dipole magnet. The bending radius of particle with charge e, energy E, and momentum p in a uniform magnetic field B is given by

$$\frac{1}{\rho} = \frac{eB}{pc} = \frac{eB}{\beta E} \tag{4}$$

where β is the relative velocity $\frac{v}{c}$ and c is the speed of light. Thus, tracks from positrons will form an angle with the beam-axis z with respect to their initial energy where particles with higher energies will have a smaller bending radius than those of lower energies. Doublets are formed considering all hits on consecutive layers that pass a pre-selection, since there is no magnetic field in the detector area the positrons will have linear trajectories and so every double needs to fulfill the following requirement shown equation 5 and Figure 3, where c is constant.

$$\frac{dx}{x_0} \approx c \qquad \text{where,} \quad dx = x_2 - x_1 \tag{5}$$

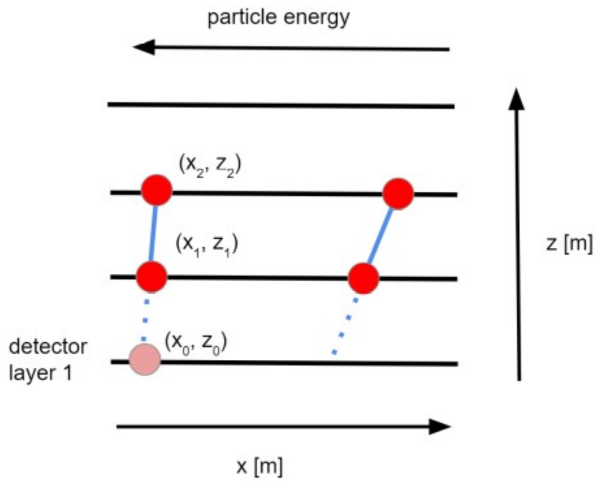

Figure 3: Formation of doublets and selection requirements

However the positrons may interact with the detector material and the detector itself isn't perfect and may not always make precise position measurements. Thus we choose an interval $\frac{dx}{x_0} \in [c - \epsilon, c + \epsilon]$. Triplets are then formed from two corresponding doublets, again since tracks should be straight,we require that corresponding doublets have an angle between them close to π. Once the triplets and doublets are selected, the optimal triplet pair candidates which can be combined to form track candidatesare then found, this selection process is done using quantum computing.

3 Quantum Computing

The optimal pairs of triplets which can be combined to form tracks, are identified using a quadratic unconstrained binary optimisation (QUBO) [2], given by

$$O = \sum_{i}^{N} \sum_{j<i} b_{ij} T_i T_j + \sum_{i=1}^{N} a_i T_i \qquad T_i, T_j \in \{0, 1\} \tag{6}$$

The QUBO is a cost function mapping to a Hamiltonian with the objective of finding the ground state, as the minimum of the function corresponds to the optimal solution which is the ground state for the Hamiltonian. The linear term of the QUBO is a characteristic term and weighs the individual triplets by their quality which is quantified by the coefficient a_i. The quadratic term is a connectivity term expressing interactions between triplet pairs, where the compatibility characterised by the coefficient b_{ij}

$$b_{ij} = \begin{cases} 0, & \text{if no shared hit (triplets do not overlap)} \\ +1, & \text{if in conflict (triplets overlap but cannot form a track candidate)} \\ -S(T_i, T_j), & \text{if forming a track candidate (triplets fully overlap)} \end{cases} \tag{7}$$

The QUBO is then mapped to an Ising Hamiltonian and solved using the Variational Quantum Eigensolver (VQE). We use VQE as it is a quantum algorithm which is resistant to noise. VQE is a hybrid algorithm which uses classical optimization while finding the ground state using quantum computing.

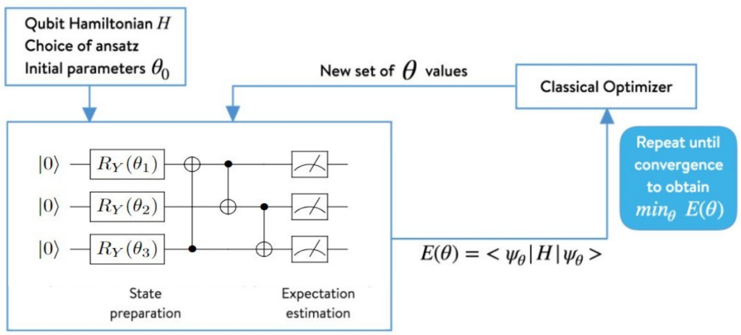

Figure 4: Diagram of VQE algorithm recreated from ref-[3]

Initial parameters are chosen classically and then put through the quantum algorithm where it performs and energy evaluation, the VQE then optimizes classically feeding in new parameters until it converges to obtain the minimum energy. VQE is useful as it can find the ground state or at least get close to it, a task challenging for a classical computer achieve [4]. However, since each triplet is mapped to a single qubit, we are limited on the number of qubits we have, as well we are limited on how many qubits IBM has available .

This study considered a simple tracking example to compare the pattern finding performance using Numpy Eigensolver (analytical solver), two quantum device simulators, where one is noise free and the another accounts for noise, and then a real quantum device provided by IBM, with the quantum devices using 7 qubits as the simple tracking example has 7 triplets. The circuit chosen uses a TwoLocal ansatz with and RY rotation gate and a Controlled Z gate, with 512 shots which is the number of evaluations with a fixed set of parameters.

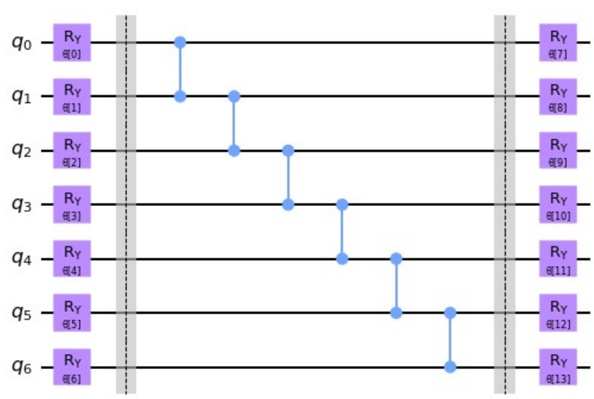

Figure 5: Circuit representation of RY and Controlled Z gate for 7 qubit TwoLocal ansatz

4 Results

The numpy Eigensolver (analytical solver) gives an exact solution which is used as a benchmark, which for our simple example is [0,0,0,1,1,1,1]. The ideal simulation, simulates a quantum device without noise where as the fake device is modelled after a real quantum device accounting noise. The results for the chosen parameters are shown in Figure 6.

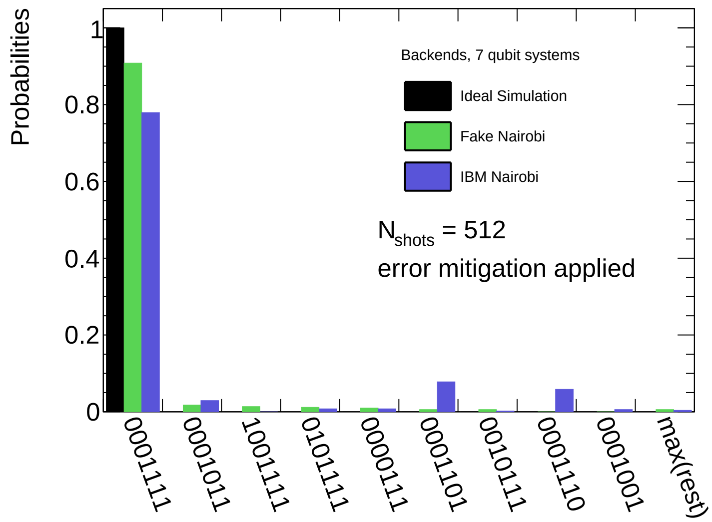

Figure 6: Comparison between ideal simulation, fake quantum device accounting for noise and the real quantum device.

We see that unlike the ideal simulation we do not get 100% accuracy for the state but a probability distribution due to noise. The fake device performs better than the real device, this indicates that it may be underestimating the amount of noise of the real device.

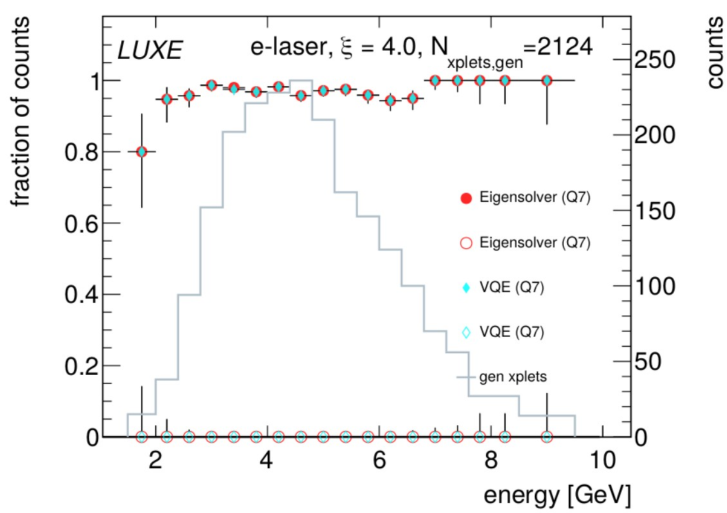

Figure 7: Efficiency vs True Energy.

For a single bunch crossing consisting of about ∼2100 particles there are more than 5000 triplets, but since we have only 7 qubits, we partition these into parts of 7 and then solve them successively. Figure 7 shows the efficiency against the particles true energy, so we still get a very high number of correct matched triplets (shaded in pointers) and a very low rate of fake triplets being matched (hollow pointers).

5 Conclusion

For my summer student project, I performed a pattern finding exercise using quantum computing with a simple tracking example. The results show that even for a simple example we don't 100% accuracy when noise is accounted for. The fake device performed better than the real device and so the fake device underestimates the amount of noise of the real device. However, using a fake device is still a sufficient place to start as it gives a useful start point to study quantum computing, and computations are much less time intensive than the real device.

References

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