IMPACT OF BEAM BACKGROUND AND JITTER ON LUXE INTERACTION POINT

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Abstract

Laser Und XFEL Experiment (LUXE) is an international project that aims to study Quantum Electro-Dynamics (QED) processes that occur in the strong field regime. Using the electron beam from the European XFEL (between 14 GeV and 17.5 GeV), this experiment will perform electron-laser and photon-laser collisions. Beamline simulations are required to understand what beam properties and backgrounds are expected at key locations like the interaction point (IP), the conversion chamber and the detectors and diagnostics. The beam optics was design and simulated with MAD-8 and this used to create a Geant4/BDSIM simulation. To perform high precision QED interactions it is crucial that the transverse size and position of the electron beam at the interaction point can be measured. The variation of the beam position over time (the beam jitter) also have an impact on the collision with the laser. This study uses simulated virtual measurement, wire scanning methods, and real measurements at the XFEL to evaluate those parameters. Finally, background from both the upstream beam line must be estimated to ensure that the impacts on the experiment are low enough. This paper present BDSIM simulations with high statistics necessary to evaluate the background.

INTRODUCTION

The European XFEL is a linear accelerator that produces high intensity X-ray photons from electrons up to 17.5 GeV. The LUXE [1] experiment want to use the EUXFEL's electrons in two setups. The first setup in Figure 1 will directly collide the electrons with a high power laser. The second setup will convert the electrons in photons and collide the later with the same laser.
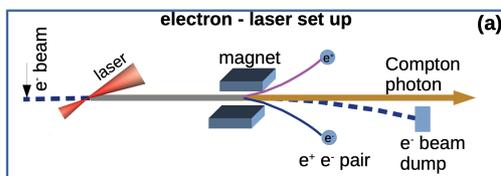

Figure 1: Schematic of LUXE's electron-laser interaction setup.

The electron bunches will be extracted from the switchyard as shown in Figure 2. A new beamline, the T20, of around 70 m has been designed from the switchyard to LUXE. A MAD-8 [3] lattice of both the transfer line (TL) and the T20 was built to provide a transverse focus at LUXE of 10 μm in x and y. From this lattice we get the twiss parameters as well as the transfer matrices for all elements. Using
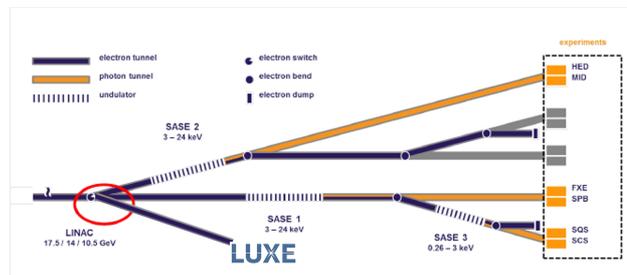

Figure 2: Top view of the EUXFEL with the future beamline leading to LUXE. Circled in red is the switchyard from which the electrons will be extracted

this MAD-8 lattice we constructed a model in BDSIM [4], a Geant4 based software for accelerator simulations. Using BDSIM we can propagate electrons to study the background interactions as well as the variation of beam position along the line.

BACKGROUNDS

vAlong the 300 m of beamline, the electron beam will interact with residual gases inside the pipe and produce backgrounds particles. Those particles could interfere with the QED [2] experiments downstream. In order to know the beam composition at LUXE's IP we need to run BDSIM simulations of an electron bunch traveling along the lattice.

When passing through this gas, the electron bunch will interact with it via three main processes : Coulomb scattering, electron bremsstrahlung and electro-nuclear interaction. Each process gives the electron a mean free path

$$\lambda = \chi \sigma n, \qquad (1)$$

where σ is the cross section of an electron for a given process, n is the number density and χ is the biasing factor we use to increase the rate.

Since the n is very low, we have to use a high χ if we want to see some background events. A dedicated study was conducted to adjust χ for each of the three processes. First to equilibrate the rate between processes and then a global biasing factor was added. The latter had to be high enough to produce background data but not to high as it will introduce more errors from the weight compensation. At the end of this study we decided on a set of biasing factor for each processes described in Table 1

Now that we have set the biasing factor for our simulations we can evaluate the beam properties with a reasonable simulation time. Running around 2×10^5 primaries and scaling for 2×10^9 electrons we can extract in Figure 3 the particle chart at LUXE's IP.

Table 1: Biasing factors used for each processes in our background simulations

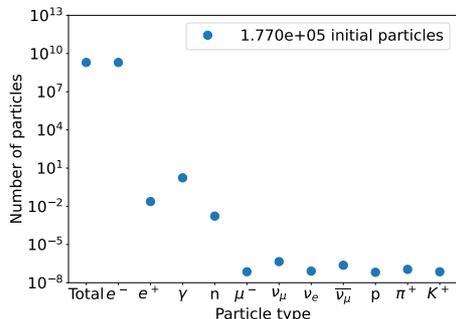| $\chi_{elec-brem}$	$\chi_{Coulomb}$	$\chi_{elec-nuc}$
2.50×10^7	1.05×10^{12}	3.70×10^{11}

Figure 3: Beam composition at LUXE's IP

Almost all the initial electrons are going through the lattice without any interaction. Other than just electrons, we see a few photons, positrons and neutrons as well as a small amount of muon neutrinos.

JITTER

In LUXE's interaction chamber, the electron beam coming from the the EUXFEL will collide with a high power laser. A good alignment of the electron beam and the laser is crucial if we want to maximize the number of particles produced by SF-QED processes. Aligning the average beam transverse position at a sub micron precision is possible with a virtual measurement. But we still expect the beam to vary from one bunch to another.

Virtual Measurement

It is possible to relate the positions x_{ref} of the electron bunches at a reference BPM to the positions of those bunches at other BPMs and a corresponding set c_{ref} of coefficients. We can establish that

$$x_{ref} = X_{ref} \cdot c_{ref} \tag{2}$$

where X_{ref} is a matrix with all the bunches position for all BPMs except the reference one.

The matrix X_{ref} can be inverted through a Singular Value Decomposition (SVD) [5] method in order to calculate the coefficients c_{ref}. This virtual measurement separates the variations in transverse position at the reference BPM in two parts. The correlated variation between bunches, what we call the position jitter,

$$\sigma_{J,ref} = \mathrm{std}(X_{ref} \cdot c_{ref}) \tag{3}$$

as well as the uncorrelated variation, what we call noise or resolution,

$$\sigma_{N,ref} = \mathrm{std}(X_{ref} \cdot c_{ref} - x_{ref}). \tag{4}$$

Measurements at the EUXFEL

In the EUXFEL switchyard, we have access to different measurement devices. The majority of them are BPMs used to measure the transverse position and charge. But there is also wire scanners for the transverse size, bunch arrival and length monitors, as well as measurements of the bunch energy. Using the data from the switchyard BPMs we can perform a virtual measurement in the existing TL, T1 and T2 beamlines. For each BPM we calculate both $\sigma_{J,ref}$ and $\sigma_{N,ref}$ in both transverse planes.
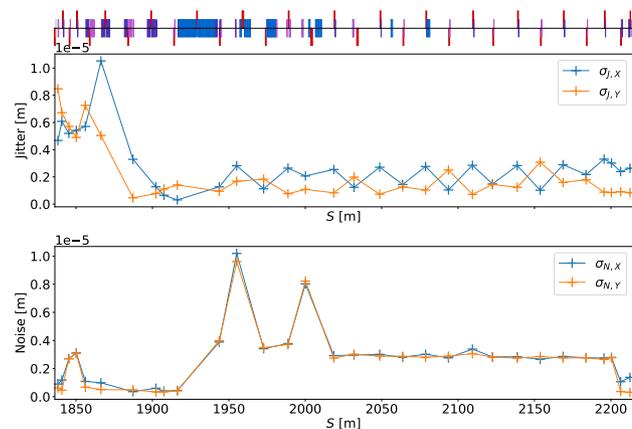

Figure 4: Virtual measurement for all the BPMs along the TL and T2 beamlines. The top plot is for the position jitter. The bottom plot is for the noise. A diagram of the lattice can be found above.

We see in Figure 4 that for electron bunches going through T2, the jitter in both planes oscillate between 1 µm and 3 µm and the noise is stable at around 3 µm. For the other parameters we can not do a virtual measurement because we do not have as many corresponding measurement devices as we have BPMs. Still we can look at the variation of those parameters over time et compute the standard deviation. All the results are stored in Table 2.

Table 2: Jitters in the EUXFEL switchyard. There is no jitter data for the beam size since wirescanners can not do bunch to bunch measurements.

	Mean	Jitter	Res.
x, y	0	1 µm-3 µm	3 µm
σ_x, σ_y	30 µm	-	3 µm
E	16.1 GeV	1 MeV	1 %
σ_t	40 fs	3.5 fs	3 fs
t	−193 fs	25 fs	1 fs

Propagation to the IP

We now have a detailed view of the electron beam in the switchyard and we want to extrapolate, from those values, the beam variations at LUXE's IP. To do this we propagate the parameters using the transfer matrix R defined as

$$(x\ x'\ y\ y'\ t\ E)^T = R_{s_0 \to s} \cdot (x_0\ x'_0\ y_0\ y'_0\ t_0\ E_0)^T \tag{5}$$

where $R_{s_0 \to s}$ is the matrix propagating the position from s_0 to s.

For the transverse position we could propagate from any BPM in our lattice. But since we want to evaluate the position at the IP, we need to find the BPMs that have a high correlation with the IP. The horizontal orbit position [6] is written as

$$x(s) = \sqrt{\beta_x(s)\varepsilon_x}\cos(\mu_x(s) + \phi) \qquad (6)$$

where μ_x is the phase advance and ϕ a constant. A correlation in position between two points in the lattice correspond to a $n\pi$ difference in phase advance with n an integer. Similarly, a correlation between the position at s_0 and the angle at s correspond then to a $n\pi + \frac{\pi}{2}$ difference in phase advance.

From the phase advance curves there is multiple correlation locations for both position and angle. To choose the most effective BPM location we need to look a the R-matrix factors at those locations and find the smallest ones. The smaller factor we have at the BPM, the higher resolution we get at the IP. From the MAD-8 R-matrices we found for each coordinate a good location in Table 3.

Table 3: BPM selection in the T20.

	S [m]	Factor
x	188.86	R_{11} =0.21
y	228.06	R_{33} =0.60
x'	271.04	R_{21} =-0.17
y'	270.56	R_{43} =-0.09

Now we can simply propagate the jitter and resolution for the transverse position using the factors in Table 3. A summary of all the jitters and noise for each parameters can be found in Table 4

Table 4: Jitters at LUXE's IP

	Mean	Jitter	Res.
x	0	0.21 µm	0.63 µm
y	0	0.6 µm	1.8 µm
x'	0	0.17 µrad	0.51 µrad
y'	0	0.09 µrad	0.27 µrad
σ_x	5 µm	-	0.45 µm
σ_y	7 µm	-	0.35 µm
E	16.1 GeV	1 MeV	1 %
σ_t	40 fs	3.5 fs	3 fs
t	0 fs	25 fs	1 fs

Ptarmigan Simulations

We know have the characteristics and variations of the electron beam at LUXE's IP. To evaluate the impact on the signal we need to simulate the collision of an electron bunch with a laser pulse. This is done with Ptarmigan [7], a Monte-Carlo simulation software for strong field interaction between a particle bunch and a laser pulse.

We simulate multiple bunches for which we vary the initial parameters to simulate jitter. Then we can see the impact $\sigma_{particle}$ of this parameter on the number of each particles produced. It is measured as the percentage ratio between the 68 % cumulative length and the average number of those particles.

Now we can repeat this set of simulations and extract all $\sigma_{particles}$ for different values of jitter and for each parameters. In the case of $\sigma_{J,x}$ we can see the results in Figure 5.
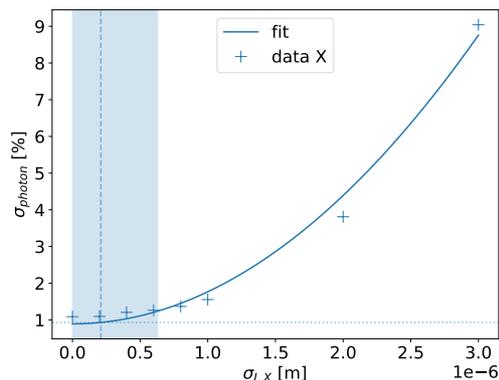

Figure 5: Impact of the jitter in x on the number of particles. The vertical band shows the region where the variation of the beam could not be differentiated from the BPM noise. The vertical line is the jitter we expect at LUXE's IP.

A jitter beyond the vertical band in those plots would be detectable from the BPMs we placed earlier. It means that a jitter in x could produce at most a 0.5 % variation on the number of each particles produced. Similarly we can see the impact of the jitter in y. The higher R-matrix factor induced a larger band so the minimum detectable jitter correspond to a variation of around 2 % on the particles.

CONCLUSIONS

The current design of the future T20 beamline has been studied through different simulations. We setup a biasing method to efficiently simulate the interactions between the electron beam and the residual gas inside the beam pipes. From this we could evaluate the impact on the beam composition, especially at LUXE's IP.

To ensure a consistent amount of QED interactions at the IP, a good overlap between the electron bunch and the laser pulse is crucial. With a virtual measurement it is possible to align the transverse beam position at sub micron levels of precision. But even with such an alignment, bunch to bunch variations will occur. This jitter we simulated varies for the transverse position between 1 µm and 3 µm which is below what we could measure at our BPMs. Simulating the electron-laser interactions with Ptarmigan we saw that the undetected jitter in the transverse position (as well as other parameters) could produce at most a 2 % variation in the signal. This variation is low enough for the experiments and confirm that the BPM setup is sufficient in the T20 beamline.

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