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ARRIVAL TIME AND ENERGY JITTER EFFECTS ON THE PERFORMANCE OF X-RAY FREE ELECTRON LASER OSCILLATOR *

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Abstract

We report on the effects of electron beam arrival time and energy jitter on the power level and the fluctuations of the output of an X-ray FEL oscillator (XFELO). For this study, we apply the FEL driven paraxial resonator model of XFELO along with an analytical reflectivity profile to mimic the phase shift and spectral filtering effects of Bragg-crystals. The thresholds for acceptable timing and energy jitters are determined in terms of the fluctuations of the steady-state power output. We explore potential ways to mitigate the XFELO power fluctuations in the presence of unavoidable jitters.

INTRODUCTION

XFELOs offer intense, stable, and coherent pulses with unprecedented spectral resolution [1–3], which would benefit measurements of various systems with increased accuracy (extending to the micro eV range) and open the possibility of adopting advanced optical techniques such as Q-switching [4], mode-locking [5], and parametric amplification, thereby bringing atomic laser properties to the X-ray regime [6].

Since XFELOs are low-gain FEL devices, their stability and performance depend on the quality and precise alignments of both electron beams and optical cavity. In a separate report [7], we applied the FEL driven paraxial resonator model of XFELO to study the effects of transverse spatial misalignments on XFELO stability. Here we prioritize longitudinal misalignment induced by fluctuations in electron beam arrival time and energy and their subsequent effects on XFELO operation and stability.

SPECTRAL FILTERING BY CRYSTALS

An optical cavity for XFELO requires at least two-Bragg crystals to form a non-tunable cavity and four crystals for a tunable one [8]. Assuming the lenses provide minimal change in the wavefront of the propagating radiation beam, the filtering effects are primarily induced by the reflecting crystals through their reflectance/reflectivity. The reflected component of the incident field $\tilde{E}^{in}(\boldsymbol{\phi}, \omega; z)$ upon interacting with a Bragg crystal is given by

$$\tilde{E}^{out}(\boldsymbol{\phi}, \omega; z) = \mathcal{R}(\boldsymbol{\phi}, \omega)\tilde{E}^{in}(\boldsymbol{\phi}, \omega; z). \quad (1)$$

Here $\mathcal{R}$ represents the reflectivity of the crystal. The tilde denotes the Fourier transformed field in the frequency-angular space. For typical XFELOs with defined radiation beam waists $\sigma_{rx,ry}$ ~10 µm and Rayleigh range z_R ≥10 m, the rms divergence of the mode matched radiation beam is $\sigma_{\phi x,\phi y}$ ≤1 µrad. Since diamond crystals considered for XFELOs usually have Darwin widths greater than 4 µm (see [8] for example), we ignore the angular filtering imposed on the radiation by the crystals for the studies reported here.

We take a step further and approximate the overall crystals' spectral effects in the cavity using a gaussian filter given by

$$\mathcal{R}(\omega) = \sqrt{R}\exp\left[\frac{-(\omega-\omega_c)^2}{4\sigma_{\text{refl}}^2} + i\,\text{atan}\left(\frac{\omega-\omega_c}{2\sigma_{\text{refl}}}\right)\right], \quad (2)$$

where R is the power reflectivity, ω_c is the central frequency and rms bandwidth in frequency space σ_{refl} is equal to 1/4 of the Darwin width. The first gaussian amplitude invokes the filter within the Darwin width and the second phase part imitates the delay effect. This expression allows us to study the crystal effects in the evolution of linear supermodes in the oscillator analytically [3, 6, 9].

For simulation studies, we consider a 200-m optical cavity formed by a two crystals and two focusing mirrors configuration (see, for example [7]). For practical considerations, we consider the net rms bandwidth of these two crystals (and hence the cavity) to be 6.87 meV. The electron beam is a relatively long bunch with low peak current achievable in an energy recovery linac and is optimized for radiation emission at fundamental wavelength λ_r =1.0298 Å (12.4 keV). Other relevant parameters are listed in Table 1.

Table 1: XFELO Parameters for Simulations

Parameter	Symbol	Value
Electron beam		
Energy	$\gamma_0 mc^2$ (GeV)	7
Energy spread	σ_γ (MeV)	1.4
Energy shift	δE (MeV)	2.3
Normalized emittance	ε_n (mm−µrad)	0.2
Peak current	I (A)	10
Pulse length	σ_t (fs)	200.0
RMS width	σ_x (µm)	12.67
Undulator/Radiation		
Undulator periods	N_u	3000
Undulator length	L_u (m)	52.8
Radiation wavelength	λ_r (Å)	1.0298
Rayleigh range	Z_R (m)	10

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JITTERS

Turn by turn arrival time jitters (ATJ) and energy jitters (EJ) are artificially generated using random number generation with pre-determined rms values. For ATJ, the rms values goes from 0 to 25 % of the e-beam rms temporal width (see Fig. 1), whereas EJ goes up to 0.013 % of the e-beam energy. In practical accelerators, many components from particle source to beam acceleration and manipulation contribute to beam fluctuations. Superconducting linacs can achieve EJs of $\Delta E/E \leq 0.01$ % and ATJs of 20 fs (corresponding to $\Delta t/\sigma_t = 10$ % for 200 fs beam) [10].

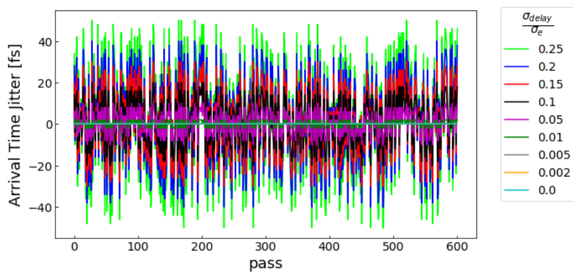


Figure 1: Plot of arrival time jitter profile per pass.

We observed how jitters affected power output and rms pulse widths after saturation (at steady-state). In an optical cavity with net power reflectivity of 85 % ($\hat{q} = R/(1-R) = 5.67$), the mean power output at saturation dropped by roughly 20 % while the fluctuations of saturated power is ~10 % of the mean power for ATJ of 25 % as shown in Fig. 2a. On the other hand, no significant change (except the blips and bumps corresponding to ATJ patterns of Fig. 1a) in rms pulse width is observed and the fluctuations stayed at or below 5 % for all ATJ values (see Fig. 2b).

In case of EJs, the power output dropped by more than 40 % at steady-state with corresponding fluctuations at the level of 10 % when EJ reached 0.013 % (Fig. 3a). Again, no noticeable change in rms pulse width is observed after saturation and fluctuations stayed at less than 1 % as shown in Fig. 3b.

MITIGATION OF JITTER EFFECTS

Since e-beam jitters are unavoidable for XFELO operation and they could adversely affect XFELO performance in terms of power output, we venture on potential ways to suppress jitter effects on XFELO's output. Since for a XFELO to sustain lasing, it must satisfy

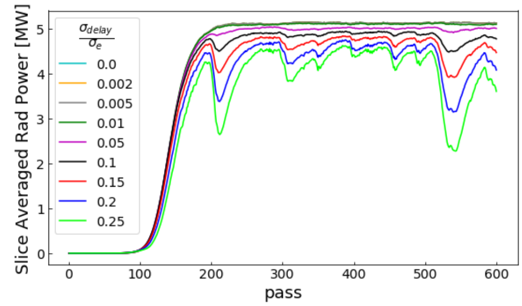
$$R(1+G) \geq 1, \tag{3}$$

where R is the net reflectivity of the optical cavity and G is the single pass FEL gain. We can tune R and G using various approach to satisfy the lasing criterion.

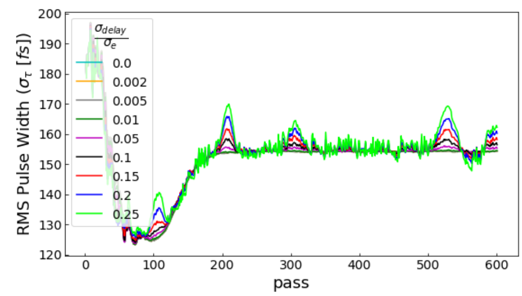
Cavity Quality

Since the first crystal in the optical cavity is made thin for outcoupling, the level of reflectivity can be adjusted by choosing a different thickness. One could employ alternate cavity designs to vary the overall reflectivity or quality factor of the cavity in hand.

Figure 4 shows normalized power fluctuations at steady-state for cavities with $\hat{q}$ ranging from 4 to 11.5 in the presence of ATJs and EJs. Higher reflective cavities (larger $\hat{q}$) led to

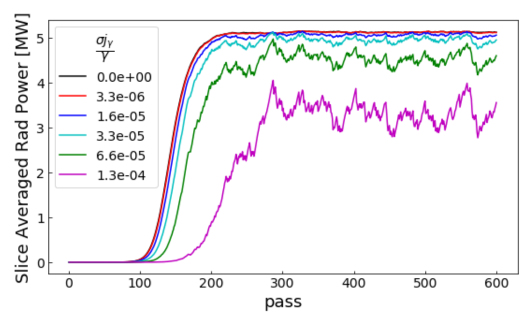


(a)

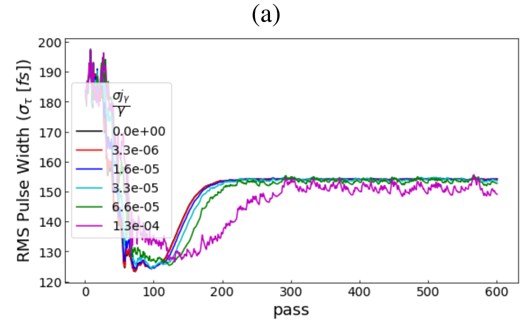


(b)

Figure 2: Plot of (a) average radiation power and (b) rms pulse width per pass for arrival time jitters with rms values from 0 to 25 % of the e-beam rms temporal width.



(a)



(b)

Figure 3: Evolution of (a) average radiation power and (b) rms pulse width per pass for energy jitters with rms value from 0 to 0.013 % of the e-beam energy.

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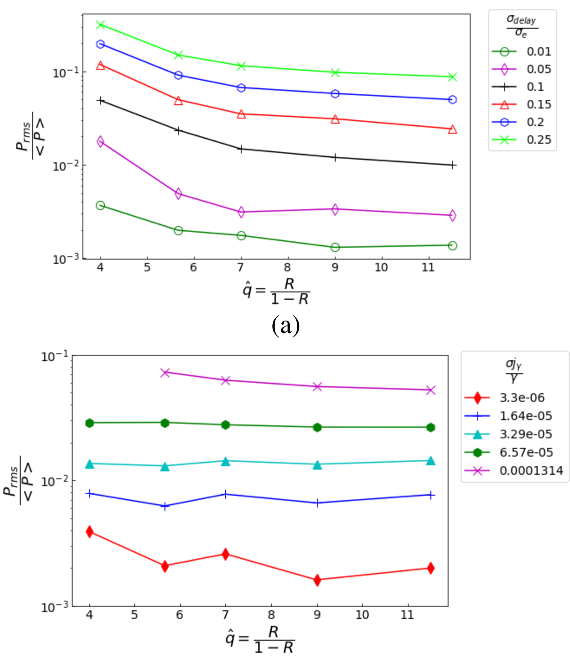

(a)

(b)

Figure 4: Normalized power fluctuations with (a) ATJ and (b) EJ for optical cavities with $\hat{q}$ between 4 and 11.5.

damping of power fluctuations by few percent in the presence of ATJ. ATJ should be restricted to within 5 %/10 % to constrain power fluctuations at steady-state around 1 %/5 %. ATJs above 15 % result in fluctuations exceeding 10 % levels. Changes in $\hat{q}$ did not lead to significant change in power fluctuations for EJs; however, the mean power output is expected to improve with increasing $\hat{q}$. EJ should be kept within 0.006 % to keep power fluctuations within 5 %. Fluctuations on the order of 10 % occurs if EJ reaches 0.01 %; at this level, the mean power output drops by more 50 % and XFELO would not sustain lasing in lossy cavity with $\hat{q} = 4$.

Constant Lasing: FEL Gain Compensation

We optimized G by adjusting beam current for the cavities considered in Fig. 4 to minimize the deleterious jitter effects in lossy cavities by keeping $R(1 + G) = 1.224$. Figure 5 shows power fluctuations obtained with ATJ. The decreased/increased gain in higher/lower quality cavity led to amplification/reduction of power fluctuations with ATJ turned ON. In fact, the power fluctuations and mean power output of lossy cavities are on par with higher quality cavities due to gain compensation. We anticipate the increased/reduced gain to result in slightly larger/smaller rms pulse width when compared to the normal cavity scan. No significant change in mean power output and power fluctuations were observed with EJ ON when compared to previous cavity quality scan. Quantitatively, previous analysis on ATJ and EJ thresholds for power fluctuations still hold.

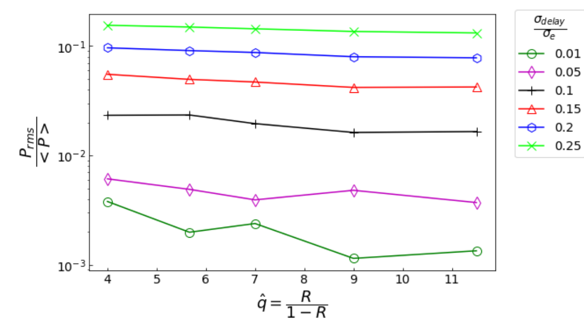

Figure 5: Normalized power fluctuations with ATJ for optical cavities of Fig. 4 at $R(1 + G) = 1.224$.

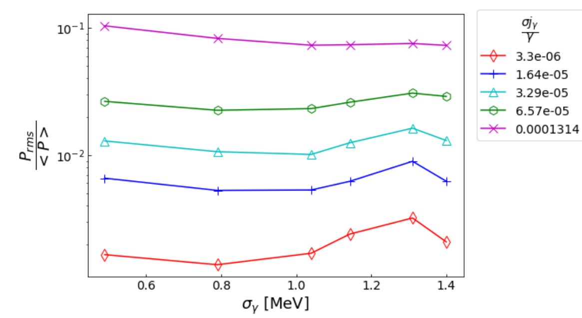

Figure 6: Normalized power fluctuations with EJ turned ON for various FELs with same gain and same cavity.

FEL Efficiency

In this approach, we optimized rms energy spread (σ_{γ}) of the e-beam and undulator periods (N_u) to keep the gain constant (in theory) for the same cavity with $\hat{q} = 5.67$. Figure 6 shows normalized power fluctuations plotted over (σ_{γ}) when EJ is ON. Although no significant quantitative change is observed for power fluctuations, some qualitative features indicate some reduction in power fluctuations for more efficient FELs (with smaller energy spread and smaller undulator length).

CONCLUSION

Our preliminary simulation results on ATJ and EJ indicate that both jitter effects can be disadvantageous for XFELO operation. ATJ above 10 % and EJ above 0.01 % can induce worrisome power fluctuations above 10 % at steady-state and should be avoided. Various approaches exploiting lasing criterion for XFELO can be used to minimize the threat of jitter effects in a desired XFELO to a certain degree without significantly altering original XFELO performance expectations. Such approaches involve changing cavity quality parameter, compensating with FEL gain, and improving FEL efficiency.

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