START-TO-END STUDY ON LASER AND RF JITTER EFFECTS FOR MAX IV SXL

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Abstract

A Soft X-ray free electron laser (FEL) for the MAX IV Laboratory is currently in the design phase and it will use the existing 3 GeV linac. Present stability limits in the RF and the photocathode laser will affect the performance of the FEL. One of the critical elements for the design of a FEL is to have an estimation on jitter effects of the accelerator parameters on the X-ray radiation. In this regard, we implemented a start-to-end study using Astra, Elegant and Genesis in order to assess possible variations in pulse energy, photon pulse length and spectral width in the Soft X-ray Laser (SXL) radiation. This investigation provides insights on the final SXL performance variation due to RF and laser related jitter affecting the electron beam.

INTRODUCTION

The Soft X-ray Laser (SXL) at the MAX IV laboratory is designed to provide high power coherent radiation in the 1–5 nm range. The MAX IV linear accelerator (linac) will drive the SXL in two main modes: the mildly compressed high-charge mode 1A and the strongly compressed low-charge short-pulse mode 1B [1]. Tables 1 and 2 shows the main parameters of the MAX IV linac and the FEL, respectively.

The possibility of being a FEL driver was included in the original design of the MAX IV linac. The linac is composed of 19 accelerating sections to bring the electron energy to 3 GeV and two 4-bend-achromats in a dogleg arrangement for bunch compression. The RF phase for the linac injector, for the first accelerating section and for the rest of the accelerating sections are set individually from each other. These three individual phases are mentioned as L00 phase, L01 phase and MDL phase in Table 1. The three RF phases are set based on a trade-off between providing a proper chirp on the beam and providing a good phase stability [2].

In this paper, after providing an explanation on the jitter study procedure, the fluctuations in the FEL radiation are investigated. A start-to-end simulation procedure is performed to investigate the electron beam shot-to-shot variation effect on the FEL radiation. Furthermore, to minimise the contribution from intrinsic SASE fluctuations, 25 different FEL shots are generated by Genesis 1.3 [3] for each beam parameter study case.

SIMULATION PROCEDURE

Table 1: Summary of Linac and Electron Beam Parameters for Two Linac Modes [2]

	1A	1B
Nominal Energy (GeV)	3	3
Bunch Charge (pC)	100	10
L00 Phase (deg)	20	20
L01 phase	26.3	24
MDL phase	0	21.5
Peak Current (kA)	3.9	3.7
FWHM Bunch Length (fs)	18	1.2

Table 2: Summary of SXL-FEL Performance for 1A and 1B Modes [2]

	1A pulse		1B pulse	
Wavelength (nm)	1	5	1	5
Total FEL length (m)	42	20	29	17
Pulse Energy (μJ)	130	220	15	20
Power (GW)	14	36	15	12
FWHM Pulse duration (fs)	9.3	5.2	0.8	1.2
FWHM Pulse BW (%)	0.5	0.7	0.36	0.8
Brightness (× $1{\times}10^{32}$)	25	10	40	1.5

The parameters which are used for the jitter study in the injector and the linac are: charge, laser arrival time, injector RF-phase, injector modulator-HV, L1 phase, L1 modulator-HV, MDL phase and MDL modulator-HV. These are the main machine parameters which can be a source of variation in the electron beam. Several start-to-end simulations were performed by varying the value of these parameters around their nominal values and looking directly at the FEL performance. The FEL performance was evaluated based on three specific parameters: FEL photon pulse energy, photon pulse length and spectral width.

In the simulation procedure the electron beam was generated and tracked along the injector by ASTRA [4], then ELEGANT [5] was used for the beam tracking along the linac. At the end the electron beam, with jitter in the specified parameter, was used as input to Genesis 1.3 and employed for investigation of the FEL radiation. The sensitivity of the three specific parameters of the FEL for different machine parameters were obtained by putting a linear fit to the Genesis data, and the slope of the linear fit was considered as the sensitivity. The three specific FEL parameters were calculated at a longitudinal position corresponding to the maximum brightness. The maximum brightness point for different radiation wavelengths and linac operation modes are specified in Table 2 as the total FEL length.

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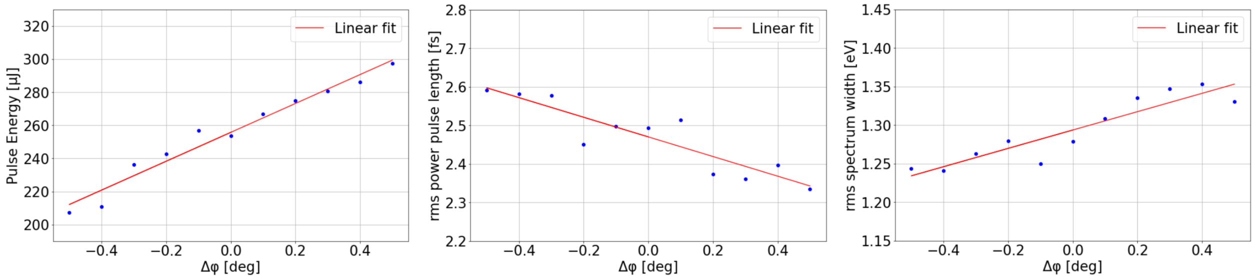

Figure 1: Variation in three specific FEL parameters due to jitter in the injector RF-phase for 1A-5nm case.

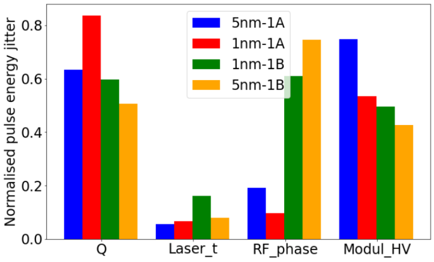

Figure 2: Comparison of normalised pulse energy from beam parameters.

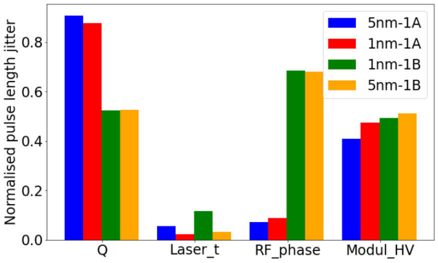

Figure 3: Comparison of normalised photon pulse length from beam parameters.

Figure 1 shows how the injector RF-phase jitter effects the 1A case at 5 nm. Each blue dot is an average of 25 shots generated by Genesis and the red line is a linear fit. The slope of the linear fit is used to obtain the sensitivity factor. The small deviation between derived data from Genesis and the linear fit which is believed to originate in the stochastic nature of the SASE radiation.

RESULTS

In this section the jitter simulation results for the FEL parameters are explained. Considering the 1 nm and 5 nm FEL radiation wavelengths and the 1A and 1B linac operation modes, the jitter study was performed on four different cases: 1A-5nm, 1A-1nm, 1B-5nm and 1B-1nm. A summary of the FEL jitter study for these four cases is given in Table 3 and it includes the jitter in pulse energy (top), photon pulse length (middle) and spectral width (bottom). The jitter in each FEL parameter is derived by multiplication of the RMS tolerance for each jitter source with the sensitivity slope.

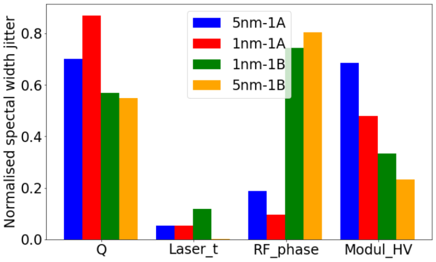

Figure 4: Comparison of normalised spectral width jitter from beam parameters.

The pulse energy jitter results in Table 3 (top) show that the 5 nm radiation case has a higher relative variation in pulse energy compared to the 1 nm radiation case. It is believed that this is due to its shorter saturation length and related to the steeper slope of the FEL gain curve. In order to a have a better comparison between jitter effects Figure 2 shows the normalised pulse energy jitter due to charge, laser arrival time, RF-phase and modulator-HV. In Fig. 2, the jitter values of injector phase, L1 phase and MDL phase are added quadratically and normalised by the total jitter value and shown as RF phase. Likewise, the jitter effects of the injector, L1 and MDL modulators are combined in Modul-HV. A similar jitter result arrangement is provided for photon pulse length and spectral width in Figs. 3 and 4 respectively.

Figure 2 shows that the major jitter effects on pulse energy for the 1A-beam are caused by charge and Modul-HV, while laser arrival time and RF-phase have a negligible effect. Also for the 1B-beam case the RF-phase and charge are the main jitter sources effecting pulse energy.

Table 3 (middle) shows that the 1A-beam has a higher relative photon pulse length variation than the 1B-beam. Nevertheless The 1B-beam has a higher relative spectral width variation in comparison to the 1A-beam (Table 3 (bottom)). Meanwhile Figs. 3 and 4 illustrate that the charge and Modul-HV are the major jitter sources for pulse length and spectral width for the 1A-beam, while for the 1B-beam the RF-phase is the main source (for the 1nm-1B RF-phase and charge have equal effect).

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Table 3: Summary of the Jitter Study for (Top) Pulse Energy, (Middle) Photon Pulse Length and (Bottom) Spectral Width

			Pulse energy - 1nm-1A			Pulse energy - 5nm-1A			Pulse energy - 1nm-1B			Pulse energy - 5nm-1B		
Beam parameters			sensitivity		Jitter(μJ)	sensitivity		Jitter(μJ)	sensitivity		Jitter(μJ)	sensitivity		Jitter(μJ)
	rms tolerance				rms			rms			rms			rms
Charge	0.01	dQ/Q	2.8E0	μJ/pC	2.80	2.0E1	μJ/pC	20.20	6.1E0	μJ/pC	0.61	1.2E1	μJ/pC	1.20
Laser arrival time	0.01	ps	2.5E-2	μJ/fs	0.25	1.6E-1	μJ/fs	1.60	1.7E-2	μJ/fs	0.17	1.9E-2	μJ/fs	0.19
Injector rf-phase	0.01	deg	2.2E1	μJ/deg	0.22	8.7E1	μJ/deg	0.87	-1.7E1	μJ/deg	-0.17	-4.0E1	μJ/deg	-0.40
Injector modulator-HV	1.0E-5	dV/V	1.7E5	μJ/dV/V	1.65	6.0E5	μJ/dV/V	6.01	2.7E4	μJ/dV/V	0.27	3.6E4	μJ/dV/V	0.37
L1 phase	0.01	deg	-6.7E1	μJ/deg	-0.67	-1.9E2	μJ/deg	-1.90	-5.0E1	μJ/deg	-0.50	-1.4E2	μJ/deg	-1.40
L1 modulator-HV	1.0E-5	dV/V	2.8E5	μJ/dV/V	2.80	1.0E6	μJ/dV/V	10.46	4.3E4	μJ/dV/V	0.43	8.5E4	μJ/(dV/V)	0.85
MDL phase	0.01	deg	4.7E1	μJ/deg	0.47	1.0E2	μJ/deg	1.02	3.3E1	μJ/deg	0.33	1.0E2	μJ/deg	1.00
MDL modulator-HV	1.0E-5	dV/V	6.1E4	μJ/dV/V	0.61	4.5E5	μJ/dV/V	4.54	-1.5E2	μJ/dV/V	-0.002	4.2E4	μJ/dV/V	0.42
Total jitter (rms)				μJ	4.422		μJ	24.127		μJ	1.021		μJ	2.372
Relative error					3.87%			10.05%			7.30%			13.18%
Nom. value (typical)				μJ	114.3		μJ	240		μJ	14		μJ	18

			Pulse energy - 1nm-1A			Pulse energy - 5nm-1A			Pulse energy - 1nm-1B			Pulse energy - 5nm-1B		
Beam parameters			sensitivity		Jitter (fs)	sensitivity		Jitter (fs)	sensitivity		Jitter (fs)	sensitivity		Jitter (fs)
	rms tolerance				rms			rms			rms			rms
Charge	0.01	dQ/Q	3.9E-2	fs/pC	-1.6E-1	-1.0E-1	fs/pC	-1.0E-1	-5.0E-2	fs/pC	-5.0E-3	-2.5E-2	fs/pC	-2.5E-3
Laser arrival time	0.01	ps	-1.0E-3	fs/fs	-1.0E-2	-2.5E-4	fs/fs	-2.5E-3	-1.1E-4	fs/fs	-1.1E-3	-1.5E-5	fs/fs	-1.5E-4
Injector rf-phase	0.01	deg	-4.6E-1	fs/deg	-4.6E-3	-2.5E-1	fs/deg	-2.5E-3	2.6E-1	fs/deg	2.6E-3	9.0E-2	fs/deg	9.0E-4
Injector modulator-HV	1.0E-5	dV/V	-2.5E3	fs/dV/V	-2.5E-2	-1.9E3	fs/dV/V	-1.9E-2	-4.1E2	fs/dV/V	-4.1E-3	1.7E2	fs/dV/V	1.7E-3
L1 phase	0.01	deg	1.1E0	fs/deg	1.1E-2	9.1E-1	fs/deg	9.1E-3	5.4E-1	fs/deg	5.4E-3	3.1E-1	fs/deg	3.1E-3
L1 modulator-HV	1.0E-5	dV/V	-6.7E3	fs/dV/V	-6.7E-2	-4.6E3	fs/dV/V	-4.6E-2	-2.3E2	fs/dV/V	-2.3E-3	1.6E2	fs/dV/V	1.6E-3
MDL phase	0.01	deg	-4.2E-1	fs/deg	-4.2E-3	-3.6E-1	fs/deg	-3.6E-3	-2.6E-1	fs/deg	-2.6E-3	-2.3E-2	fs/deg	-2.3E-4
MDL modulator-HV	1.0E-5	dV/V	6.3E1	fs/dV/V	6.3E-4	-2.0E3	fs/dV/V	-2.0E-2	-2.5E1	fs/dV/V	-2.5E-4	6.9E1	fs/dV/V	6.9E-4
Total jitter (rms)				fs	**0.176**		fs	**0.114**		fs	**0.01**		fs	**0.005**
Relative error					**5.17%**			**4.39%**			**2.72%**			**0.95%**
Nom. value (typical)				fs	**3.41**		fs	**2.6**		fs	**0.35**		fs	**0.5**

			Pulse energy - 1nm-1A			Pulse energy - 5nm-1A			Pulse energy - 1nm-1B			Pulse energy - 5nm-1B		
Beam parameters			sensitivity		Jitter(eV)	sensitivity		Jitter(eV)	sensitivity		Jitter(eV)	sensitivity		Jitter(eV)
	rms tolerance				rms			rms			rms			rms
Charge	0.01	dQ/Q	3.9E-2	eV/pC	3.9E-2	2.4E-2	eV/pC	2.4E-2	1.5E0	eV/pC	1.5E-1	9.4E-1	eV/pC	9.4E-2
Laser arrival time	0.01	ps	-3.0E-4	eV/fs	-3.0E-3	1.5E-4	eV/fs	1.5E-3	3.1E-3	eV/fs	3.1E-2	4.1E-5	eV/fs	4.1E-4
Injector rf-phase	0.01	deg	2.4E-1	eV/deg	2.4E-3	1.2E-1	eV/deg	1.2E-3	-7.4E0	eV/deg	-7.4E-2	-4.8E0	eV/deg	-4.8E-2
Injector modulator-HV	1.0E-5	dV/V	8.5E2	eV/dV/V	8.5E-3	9.4E2	eV/dV/V	9.4E-3	3.9E3	eV/dV/V	3.9E-2	2.5E3	eV/dV/V	2.5E-2
L1 phase	0.01	deg	-9.4E-1	eV/deg	-9.4E-3	-2.0E-1	eV/deg	-2.0E-3	-1.7E1	eV/deg	-1.7E-1	-1.3E1	eV/deg	-1.3E-1
L1 modulator-HV	1.0E-5	dV/V	2.6E3	eV/dV/V	2.6E-2	7.4E2	eV/dV/V	7.4E-3	7.7E3	eV/dV/V	7.7E-2	3.0E3	eV/dV/V	3.0E-2
MDL phase	0.01	deg	-3.6E-1	eV/deg	-3.6E-3	1.2E-1	eV/deg	1.2E-3	6.4E0	eV/deg	6.4E-2	1.7E0	eV/deg	1.7E-2
MDL modulator-HV	1.0E-5	dV/V	-2.6E3	eV/dV/V	-2.6E-2	-5.6E2	eV/dV/V	-5.6E-3	1.8E3	eV/dV/V	1.8E-2	1.0E3	eV/dV/V	1.0E-2
Total jitter (rms)				eV	**0.055**		eV	**0.028**		eV	**0.264**		eV	**0.171**
Relative error					**1.24%**			**2.12%**			**7.13%**			**9.52%**
Nom. value (typical)				eV	**4.46**		eV	**1.3**		eV	**3.7**		eV	**1.8**

CONCLUSION

In this paper we considered the effects of jitter in the accelerator system on the three specific FEL radiation parameters; pulse energy, pulse length and spectral width. The jitter effects were investigated through a start-to-end simulation study. The simulation results show that charge and modulator-HV are the main jitter sources for the 1A-beam (high charge - medium compressed) and RF-phase is the main jitter source in the 1B-beam (low charge - strongly compressed) for all the three FEL parameters. Thus, reaching the specified RMS tolerances for the charge, RF-phase and, especially, the modulator-HV is a high priority for a stable FEL operation.

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