S2E SIMULATIONS ON JITTER FOR EUROPEAN XFEL PROJECT

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Abstract

To generate stable SASE sources at the European XFEL facility, we should supply high quality electron beams with constant beam characteristics to around 250 m long undulator. Generally, electron and photon beam parameters such as peak current, bunch arriving time, and SASE source saturation power are significantly dependent on RF phase and voltage jitters of linac and current jitter of magnet power supplier for bunch compressor. In this paper, we describe start-to-end (S2E) simulations on jitter in the new linac layout for the European XFEL project.

INTRODUCTION

Recently, we have designed a new linac layout for the European XFEL project to control the microbunching instability [1]. According to our S2E simulations, the new linac layout has much weaker strength of the microbunching instability, and all obtained electron beam parameters are much better than our requirements for the European XFEL project [1]. Since our new linac layout has only one bunch compressor (BC) stage with a double chicane, its jitter tolerance may be tight [2]. At the TESLA Test Facility Phase 2 (TTF2), over 60 seconds, controllable rms current error $\Delta I/I$ of magnet power supplier, rms phase error $\Delta\phi$ of all RF systems, and rms voltage error $\Delta V/V$ of all RF systems are within about 0.02%, 0.1 deg, and 0.03%, respectively. Therefore jitter tolerances of the new layout should be close to our current controllable ones. In this paper, we describe S2E simulations on jitter sensitivity, jitter tolerance, and the influence of jitter on FEL performance in the new linac layout for the European XFEL project.

S2E SIMULATION RESULTS

Jitter Sensitivity and Tolerance

Generally, bunch length σ_z and bunch arriving time T_a are sensitive to RF phase error $\Delta\phi$ in the precompressor linac. This tight phase tolerance in precompressor linac becomes looser if we use more klystrons at the upstream of bunch compressor as shown in Fig. 1, where a number in each RF component indicates the total dedicated klystron for the RF component. Therefore two klystrons will be used in the first TESLA superconducting module (ACC1) and the 3rd harmonic TESLA module (ACC39). To investigate the jitter sensitivity J_s and jitter tolerance J_t of the European XFEL project, we have performed start-to-end (S2E) simulations with ASTRA and ELEGANT codes. By applying an artificial jitter or error to each component, then by monitoring its effects at the end of linac, we can determine the jitter sensitivity of the component. Here we assume that jitter is uncorrelated, and all components do not have any misalignment.

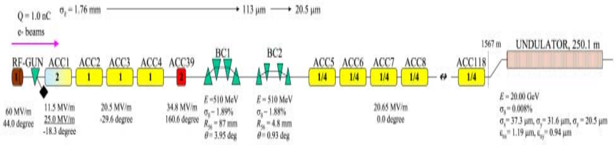

Figure 1: New linac layout for the XFEL project.

After considering our current controllable tolerances at TTF2, we have used following four constrains in determining the jitter sensitivity: First, change in rms bunch length with respect to the ideal case without any jitter $\Delta\sigma_z/\sigma_{z\mathrm{o}} = (\sigma_z - \sigma_{z\mathrm{o}})/\sigma_{z\mathrm{o}}$ should be within 10%. From now on, parameters with (without) subscript o correspond to the obtained values when jitter is zero (nonzero), and parameters with subscript 0 indicate their average values. Second, change in bunch arriving time with respect to the ideal case $\Delta T_{\mathrm{arrival}} = T_a - T_{a\mathrm{o}}$ should be within 50 fs. Third, change in average beam energy with respect to the ideal case $\Delta E/E_\mathrm{o} = (E_0 - E_{0\mathrm{o}})/E_{0\mathrm{o}}$ should be within 0.005%. Fourth, change in relative peak-to-peak (p2p) energy deviation with respect to the ideal case $\Delta\delta = dE_{p2p}/E_0 - (dE_{p2p}/E_0)_\mathrm{o}$ should be within 0.1%.

The most sensitive jitter source in rms bunch length, bunch arriving time, and relative p2p energy deviation is the phase error $\Delta\phi$ in precompressor linacs from ACC2 to ACC4. Since ACC2, ACC3, and ACC4 will be operated by their own klystrons under the same RF conditions, three phase errors in three klystrons give the same sensitivity as shown in Fig. 2. And the most sensitive jitter source in average beam energy is the voltage error $\Delta V/V$ in postcompressor linacs from ACC5 to ACC118. Since one klystron is dedicated to four sequent TESLA superconducting modules in postcompressor linacs, total 29 klystrons will be used in postcompressor linacs as shown in Fig. 1. Therefore 29 voltage errors in 29 klystrons give the same sensitivity as in Fig. 2. According to above four constrains, the final determined jitter sensitivities of phase error in precompressor linacs and voltage error in the postcompressor linacs are -0.06 deg and 0.03%, respectively.

By repeating above processes, we have determined jitter sensitivities and jitter tolerances of all components, which satisfy a relation of $\sqrt{\sum_{i=1}^{n}(J_t/J_s)^2} < 1$. Here n is the total number of all considered components [2]. Investigated bunch-to-bunch rms jitter sensitivities and jitter tolerances are summarized in Table 1 [3], [4]. Here all tolerances in the first tolerance set TOL-I are more

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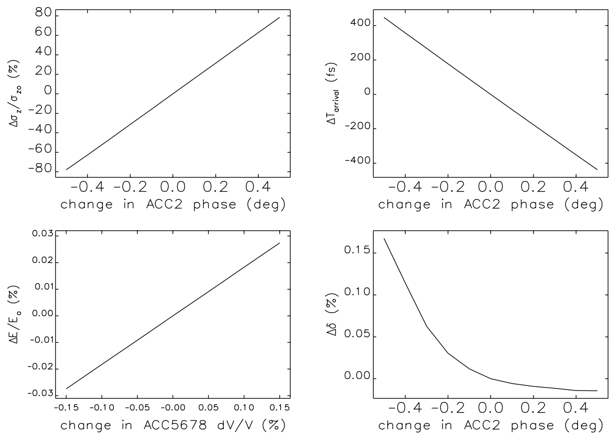

Figure 2: The most sensitive jitter source in rms bunch length (top left), bunch arriving time (top right), average beam energy (bottom left), and relative p2p energy deviation (bottom right).

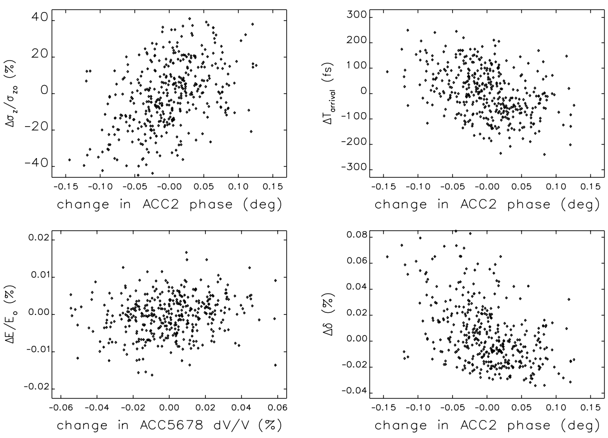

Figure 3: Scattering plots of rms bunch length (top left), bunch arriving time (top right), average beam energy (bottom left), and relative p2p energy deviation (bottom right) versus the most sensitive jitter sources for 400 times S2E simulations under tolerance set TOL-I.

Table 1: Jitter sensitivity and tolerance for XFEL project.

Jitter parameter	Unit	Sensitivity	TOL-I	TOL-II
gun timing ΔT	ps	0.50	0.10	0.30
charge $\Delta Q/Q$	%	-6.10	1.00	1.50
ACC1C1234 $\Delta\phi$	deg	0.20	0.05	0.07
ACC1C1234 $\Delta V/V$	%	-0.17	0.02	0.03
ACC1C5678 $\Delta\phi$	deg	0.10	0.05	0.07
ACC1C5678 $\Delta V/V$	%	-0.08	0.02	0.03
ACC234 $\Delta\phi$	deg	-0.06	0.05	0.07
ACC234 $\Delta V/V$	%	-0.06	0.02	0.03
ACC39 $\Delta\phi$	deg	-0.08	0.05	0.07
ACC39 $\Delta V/V$	%	0.19	0.02	0.03
BC1 $\Delta I/I$	%	0.02	0.02	0.02
BC2 $\Delta I/I$	%	0.31	0.02	0.02
ACC5678 $\Delta\phi$	deg	4.19	0.05	0.07
ACC5678 $\Delta V/V$	%	0.03	0.02	0.03

tighter than those in the second tolerance set TOL-II, which is close to our current controllable tolerances at TTF2, ACC1C1234 (ACC1C5678) indicates the first (last) four cavities in ACC1 module with a lower (higher) gradient, ACC234 means any one TESLA module from ACC2 to ACC4, and ACC5678 indicates any four sequent TESLA modules from ACC5 to ACC118 which are linked with one identical klystron.

LINAC and FEL Performance under Jitter

To investigate linac and FEL performance under one jitter tolerance set, we have performed S2E simulations with ASTRA and ELEGANT codes. After applying one error set to all components, which is randomly and Gaussianly distributed within $\pm(3.0 \times \mathrm{tolerance\,set})$ range, we have tracked the whole European XFEL linac with 50000 macroparticles. Here ASTRA code is used to consider space charge force at the gun region, and ELEGANT code is used to consider coherent synchrotron radiation in BCs and geometric wakefields in all superconducting modules. By repeating this S2E simulation 400 times with randomly distributed different error sets which are within $\pm(3.0 \times \mathrm{tolerance\,set})$, we have obtained statistical information on linac performance. In the case of S2E simulations under tolerance set TOL-I, scattering plots of rms bunch length, bunch arriving time, average beam energy, and relative p2p energy deviation versus the most sensitive jitter sources are shown in Fig. 3. Since the rms tolerance of phase error in ACC2, ACC3, and ACC4 modules is 0.05 deg, and the rms tolerance of the voltage error in any four sequent TESLA modules at the downstream of BCs is 0.02% for tolerance set TOL-I, rms errors or variations in rms bunch length, bunch arriving time, average beam energy, and relative p2p energy deviation with respect their median values are around 20%, 100 fs, 0.005%, and 0.025%, respectively as shown in Fig.3. Since variations in bunch length and bunch arriving time is somewhat large, the phase jitter in the precompressor linacs should be improved further. In the case of variation in bunch arriving time, that will be more smaller if we can reduce its original source, gun timing jitter of 100 fs.

By analyzing those 400 times S2E simulation results with the Ming Xie model, we have obtained statistical information on FEL performance under two tolerance sets as shown in Figs. 4 and 5, and as summarized in Table 2. Here FEL performance is estimated with 41 slices, 80% (100%) indicates that only 80% core (whole 100%) slices are used to obtain the slice-averaged parameter, and left (right) thing in each column corresponds to the median value (the rms error or variation with respect to the median value) of obtained 400 times S2E simulation results. Since the most

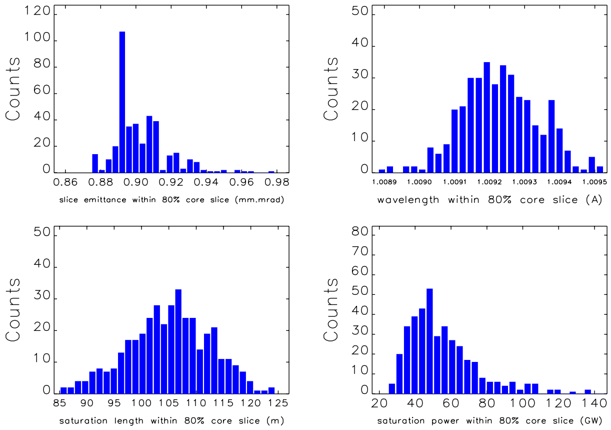

Figure 4: 1D histograms on FEL performance for 400 times S2E simulations under tolerance set TOL-I: slice horizontal emittance in 80% core (top left), SASE source wavelength in 80% core (top right), SASE source 3D saturation length in 80% core (bottom left), SASE source saturation power in 80% core (bottom right).

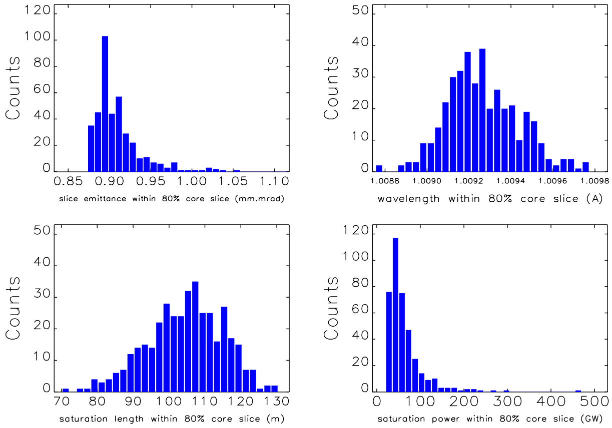

Figure 5: 1D histograms on FEL performance for 400 times S2E simulations under tolerance set TOL-II: slice horizontal emittance in 80% core (top left), SASE source wavelength in 80% core (top right), SASE source 3D saturation length in 80% core (bottom left), SASE source saturation power in 80% core (bottom right).

parts of slice emittance, SASE light source wavelength, and 3D saturation length are distributed around their median values, their variations are small as shown in Figs. 4 and 5. But rms variation in saturation power is about 40% (90%) for tolerance set TOL-I (TOL-II) as shown in Figs. 4 and 5. These large variations in saturation power can be improved further by reducing the gun timing jitter, phase jitter in the precompressor linacs, and voltage jitter in the postcompressor linacs. Recently, it was reported that gun timing jitter can be reduced to sub-fs range by new Laser-RF synchronizing and timing technologies [5]. And in the case of phase and voltage jitters, those jitters can be improved further by reducing fluctuation in single bunch charge which is strongly related to phase and energy errors of gun driving laser and voltage error of gun RF system. Therefore, first of all, gun driving laser should be stabilized to improve phase and voltage jitters of RF systems.

Table 2: Linac and FEL performance under jitter tolerance.

Parameter	Unit	TOL-I	TOL-II
rms bunch length	μm / %	19.11 / 19	18.98 / 26
bunch arriving time	μs / fs	5.218 / 95	5.218 / 125
average beam energy	GeV / %	20 / 0.005	20 / 0.008
rms rel. energy spread	10^{-5} / %	8.0 / 0.002	8.1 / 0.004
hor. centroid position	μm / %	5.01 / 198	6.92 / 236
hor. centroid angle	10^{-8} / %	-4.2 / 273	-6.4 / 320
ver. centroid position	10^{-8} / %	-4.8 / 0.05	-4.8 / 0.08
ver. centroid angle	10^{-9} / %	1.77 / 0.06	1.77 / 0.09
80% slice hor. emittance	μm / %	0.886 / 1.7	0.888 / 3.6
80% light wavelength	Å / %	1.009 / 0.01	1.009 / 0.02
80% 3D sat. length	m / %	105.5 / 7.1	105.3 / 10.1
100% 3D sat. length	m / %	145.1 / 5.0	144.8 / 7.2
80% sat. power	GW / %	50.4 / 41	51.1 / 89
100% sat. power	GW / %	41.8 / 40	42.4 / 86

SUMMARY

By the help of S2E simulations with ASTRA and ELEGANT codes, we have investigated bunch-to-bunch jitter sensitivity, jitter tolerance, and the influence of jitter on FEL performance in the new linac layout for the European XFEL project. Since the new linac layout has only one BC stage with a double chicane, rms bunch length, bunch arriving time, and saturation power of SASE source have somewhat large variations under jitters. In the case of jitter tolerance set TOL-II, which is close to our current controllable tolerances at TTF2, those variations become more larger. We expect that those large variations may be improved further by the new developing technologies which can reduce the gun timing jitter, phase jitter in the precompressor linacs, and voltage jitter in the postcompressor linacs. Now we are under designing another linac layout with two BC stages. After considering obtainable beam parameters, microbunching instability, and jitter tolerances, we will determine the final linac layout for the European XFEL project.

REFERENCES

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