TOLERANCES FOR A SEEDED FREE ELECTRON LASER*

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Abstract

Tolerance and stability are important issues for designing and operating accelerator and FEL. Jitter can come from various sources. We identify and study well-known sources as well as some particular ones, important for a seeded tapered high power FEL. Seed laser phase error, electron bunch current profile, self-seeding residual density bunching and energy modulation after the chicane, and undulator wakefield are just a few important examples.

INTRODUCTION

The Linac Coherent Light Source (LCLS), the most powerful operating source of transversely coherent, few to hundred femtosecond pulse duration, X ray Free Electron Laser (FEL) [1], offers novel ways to study the structure and dynamics of atomic and molecular system. LCLS is becoming more attractive because of the recent upgrade to have self-seeding functionality [2]. Recent work has demonstrated narrow bandwidth source in such a self-seeding scheme, but also the limitations of this method, including expected large intensity fluctuations associated with shot-to-shot changes in electron beam energy and current distribution [3]. How to overcome these issues become critical. In fact, tolerance and stability are important in general for designing and operating accelerator and FEL due to various jitter sources in such complicated systems. Here we discuss well-known sources as well as some particular ones, important for a seeded tapered high power FEL.

For a Seeded FEL (SFEL), one has to study the imperfectness of the seed laser and how it affects the FEL performance. For this regard, we look at seed laser imperfection in its chirp, curvature, and modulation. In fact, the electron bunch can also have energy chirp, curvature, and modulation which are seen in start-to-end simulation. Due to the accelerator system jitter, *e.g.*, RF jitter and compressor jitter, the electron bunch properties will jitter in energy, the pulse duration, and current profile. Besides these bunch global properties, the electron bunch slice properties also varies from slice to slice, which will affect the phase coherence in a SFEL, and therefore, affect the SFEL intrinsic bandwidth. For a self-seeding FEL (SSFEL), some additional issues can be important, *e.g.*, the temporal and spatial overlap of the seed and the electron bunch at the beginning of the second undulator. Furthermore, the by-pass chicane can greatly smear out the density microbunching generated from the SASE process in the SASE FEL, yet, it normally does not smear out the residual energy modulation along the electron bunch. Such residual energy modulation will be further converted into density modulation due to the R_{56} in the by-pass chicane and the R_{56} in the SFEL undulator. These effects from the residual modulation call for a scheme to use a fresh bunch in the SFEL undulator. Using a dominant coherent seed with large signal-to-noise ratio, the SFEL undulator can be tapered after the exponential growth saturation point to further amplify the FEL to high power at the terawatts (TW)-level. However, such a high tapered undulator system requires a stable electron bunch both in the centroid energy and the current profile. Jitter in accelerating phase can largely affect the tapered FEL performance; hence tolerance on the jitter becomes very stringent.

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EFFECTS OF VARIOUS IMPERFECTNESS AND JITTER

In the following, we discuss more details, which should be studied to budget the tolerance of a SFEL. The simulation is done with three codes: *GENESIS* [4] for the FEL simulation, *IMPACT-T* [5] for the injector dynamics and *elegant* [6] for the LINAC beam dynamics.

Seed Laser Imperfectness

In a SFEL, the undulator strength jitter or the electron centroid energy jitter will translate into amplification efficiency of the seed, if the seed is perfect as shown in Fig. 1, where the undulator parameter variation is $\Delta a_w/a_w$ = ±5E-04. Thinking this as the variation in electron centroid energy, we are essentially seeing the well-known detuning theory.

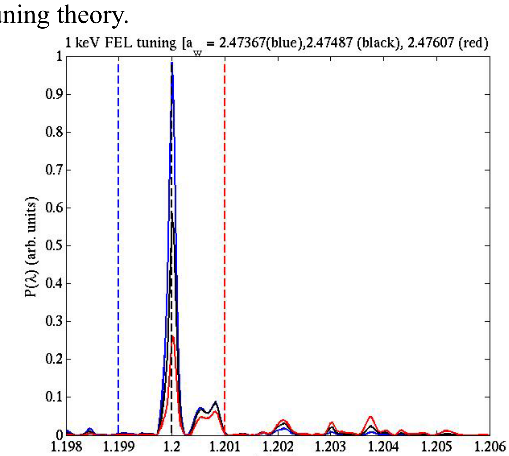

Figure 1: A SFEL subject to a variation of a_w: $\Delta a_w/a_w$ = 5E-04 (red), 0 (black), and -5E-04 (blue).

In contrast to a perfect seed with a bandwidth narrower than the FEL amplification bandwidth, if the seed has a chirp of 0.1 % over the seed duration, the effective bandwidth of the seed is now wide enough as compared with the FEL amplification bandwidth in our example. In this case, rather than what is predicted by the detuning theory, *i.e.*, the SFEL wavelength is fixed, the amplification frequency peak can be no longer at the seed

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wavelength, but at the FEL amplification peak as shown in Fig. 2, where again a same amount of variation of the undulator parameter is introduced.

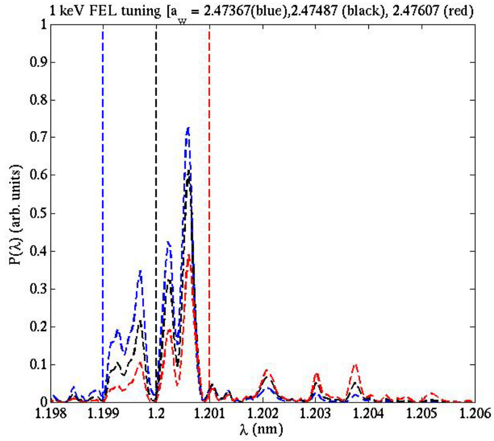

Figure 2: A SFEL with a chirp seed subject to a variation of a_w: $\Delta a_w/a_w$ = 5E-04 (red), 0 (black), and -5E-04 (blue).

RF Phase Jitter

Now let us look at the effects of the RF jitter. We here use LCLS Hard X-Ray Self-Seeding (HXRSS) as a concrete example. Using a downstream spectrometer, we can measure the energy profile of the LCLS electron bunch as shown in Fig. 3, which is a map [7] of the longitudinal current profile of the LCLS electron beam.

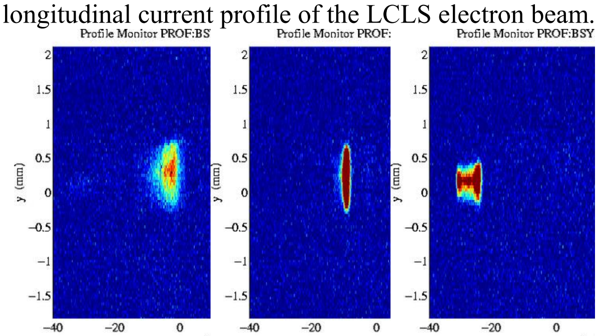

Figure 3: Longitudinal phase space measurement of the LCLS electron bunch: over-compression (left), up-right (middle), and under-compression (right).

Using the method above, we measure the shot-to-shot current profile of the electron bunch. Typical shot-to-shot variation is shown in Fig. 4. The RF jitter changes not only the compression factor, thus the electron bunch duration, but also the current profile, in particular, the double-horn distribution, besides the centroid energy.

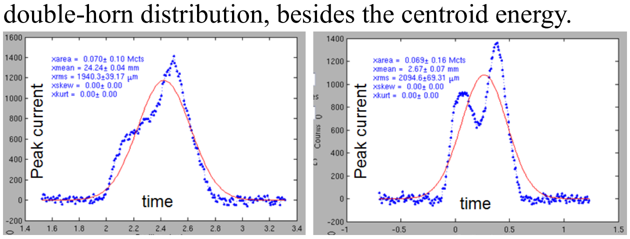

Figure 4: Typical variation of the current profile of the LCLS electron bunch.

The change of the electron centroid energy leads to a detuning effect on a seeded FEL, hence changes the efficiency, and leads to a fluctuation in the FEL power. The change in the electron bunch length and current profile on the other hand changes the FEL bandwidth. We illustrate these with a concrete example. In LCLS configuration, the L1S and L1X before the BC1 provide the energy chirp on the electron bunch, and with proper design, cancel the second order energy curvature on the electron bunch so to linearize the electron bunch longitudinal phase space. We introduce ±0.5° S-band degree in L1S phase and ±0.5° X-band degree in L1X phase. The FEL performance for various cases due to these phase jitter sources are shown in Fig. 5.

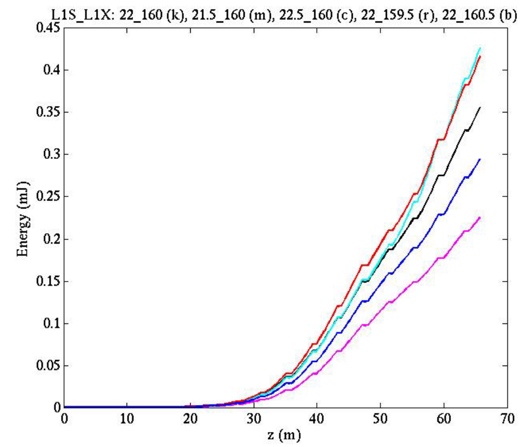

Figure 5: RF phase jitter (L1S and L1X) induced FEL energy fluctuation. Colour map is in Table 1.

To quantify the different contribution, we use a constant seed power of 1 MW and profile, but let L1S and L1X phase jitter as in Table 1. The starting point of the *x*-axis in Fig 5 stands for the beginning of the SFEL undulator. To extract as much power as possible, the taper is optimized to start at 30 m and have a total amount of 0.4 % from 30 m to the undulator end (65.7 m). The FEL energy varies from about 0.2 to 0.4 mJ as detailed in Table 1.

Table 1: Different Cases with RF Jitter

L1S	L1X	Colour	FEL energy (mJ)
22	160	black	0.356
22	159.5	red	0.417
22	160.5	blue	0.295
21.5	160	magenta	0.225
22.5	160	cyan	0.427

RF jitter causes the jitter in the compression factor, therefore the FEL pulse duration varies as shown in Fig. 6. Besides, the RF jitter causes a jitter in the electron centroid energy, therefore affects the amplification efficiency as in detuning theory. Furthermore, due to the residual energy chirp along the electron bunch, the self-seeding dictated seed frequency will unavoidably be resonant to different part of the electron bunch; therefore, different part of the electron bunch will amplify the seed.

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This is seen in Fig. 6. The FEL temporal profile varies dramatically.

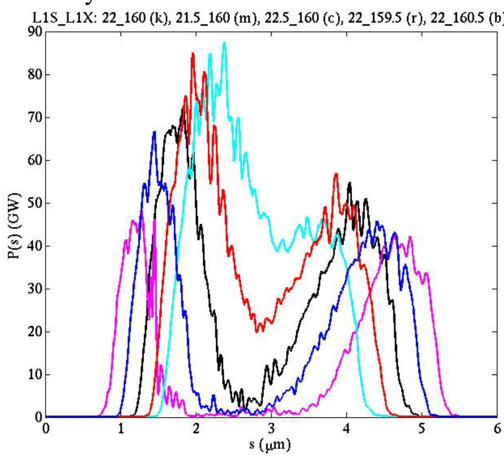

Figure 6: RF phase jitter (L1S and L1X) induced FEL pulse duration and temporal profile fluctuation. Colour map is in Table 1.

A direct consequence is the variation of the FEL bandwidth as shown in Fig. 7, where the spectrum profile can significantly change. Hence, maintain a stable machine is crucial for a stable SFEL performance.

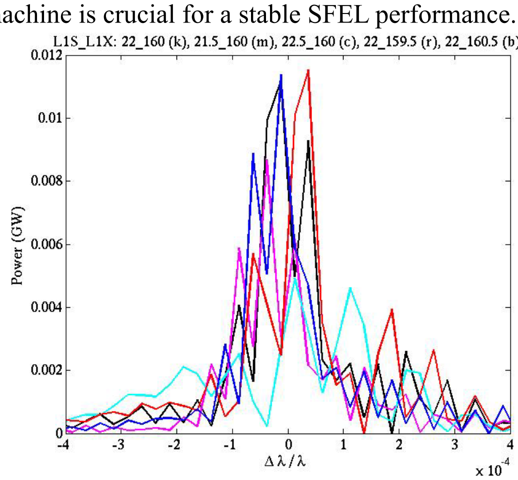

Figure 7: RF phase jitter (L1S and L1X) induced FEL spectrum bandwidth fluctuation. Colour map is in Table 1.

It is worthwhile to mention that here we use a constant seed of 1 MW, but in reality the seed power follows a negative-exponential distribution, and inherently 100 % fluctuation in the initial seed power. This coupling to the RF jitter of the machine can make the final FEL power fluctuate more.

Residual Energy Modulation in Self-Seeding FEL

In a self-seeding scheme, noticeable microbunching has been built up in the electron bunch in the SASE FEL undulator. The by-pass chicane can smear out the microbunching due to Landau damping. However, the energy modulation imprinted by the SASE process still exists, hence due to the R_{56} in the by-pass chicane and the R_{56} in the seeded undulator itself, the energy modulation is converted into density modulation and hence coherent start-up is seen in seeded FEL undulator as shown in Fig. 8 as the green curve. As a comparison, a fresh bunch case, *i.e.*, assuming that we introduce a fresh bunch into the second undulator to start the amplification process is shown as the blue curve in Fig. 8. Also, a quiet start-up in a steady-state simulation is shown as the red curve.

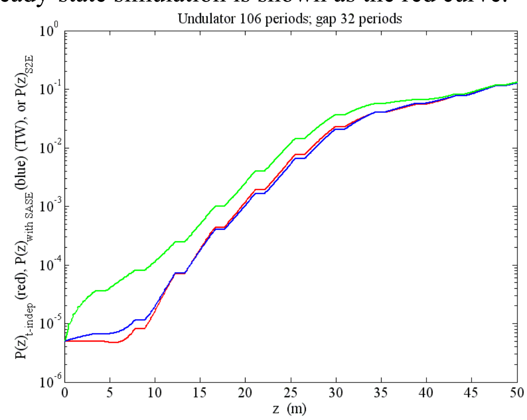

Figure 8: Coherent start-up due to residual bunching after the self-seeding chicane (green) as compared to SASE start-up (blue) due to noise and steady-state (red) quiet start-up.

Due to the factor that this residual energy modulation is generated from the SASE process, the start-up of the self-seeding FEL is subject to another source of fluctuation. As a consequence, this introduces another source of fluctuation in the respond to an optimized taper profile [4-7]. This also leads to an earlier saturation of a tapered FEL as shown in Fig. 9, where the colour map is the same as in Fig. 8.

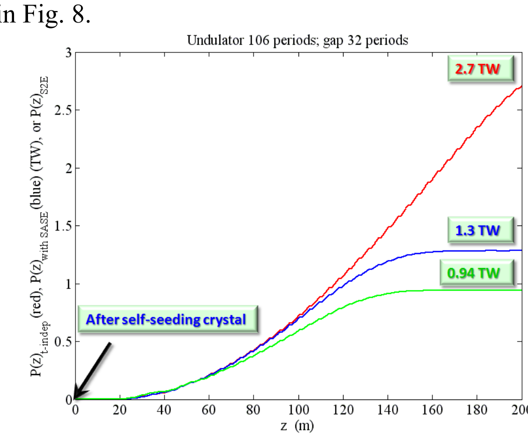

Figure 9: Saturation of a TW-level FEL. Colour map is the same as that in Fig. 8.

Undulator Wakefield Effect

In the small gap undulator, the resisitive-wall wakefield together with other source of wakefield introduces an additional energy chirp on the electron bunch. As a concrete example, an electron bunch having double-horn current profile and compressed to 2.5 kA is shown in Fig. 9 with the longitudinal phase space shown in Fig. 10, where an energy chirp is seen where the electron bunch head is to the left. The wakefield will make the tail part of the electron lose more energy, hence the wakefield

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induced energy chirp will compensate the initial energy chirp in this particular case as detailed in Fig. 12.

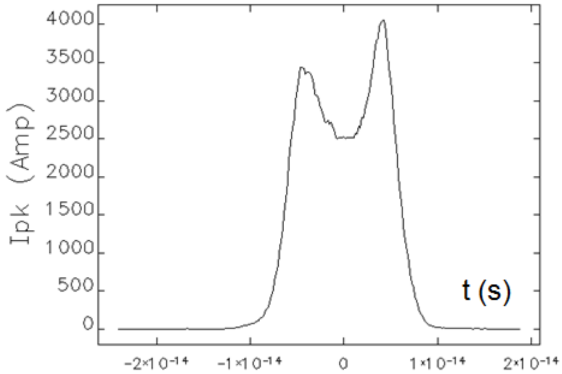

Figure 10: A double-horn current profile of the LCLS electron bunch compressed to 2.5 kA at the center.

The top curve in Fig. 12 stands for the current profile as in Fig. 10. The below 8 curves are the centroid energy of each slice. Notice that as compared to Fig. 10 and Fig. 11 where the horizontal axis of in time, the horizontal axis in Fig. 12 is s in units of μm. Hence, the head is to the right.

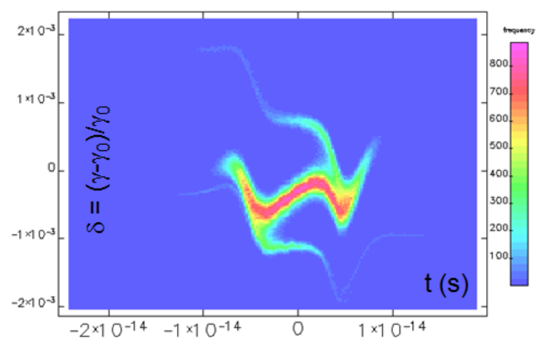

Figure 11: The longitudinal phase space showing an energy chirp along the bunch.

The set of 8 curves in Fig. 12 shows the rotation of the electron bunch longitudinal phase space. From top to bottom, the curve stands for the slice centroid energy at 0, 10, 20, 30, 40, 50, 60, and 65.7 m into the seeded untulator. The effect of wakefield compensating the initial energy chirp is clearly seen.

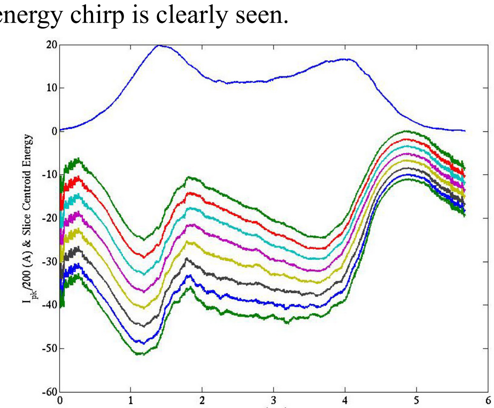

Figure 12: The wakefield induced energy chirp compensates the initial energy chirp along the electron bunch.

The energy chirp along the electron bunch couples to the R_{56} in the seeded undulator will lead to compression or decompression of the FEL wavelength as shown in Fig. 13. In this case, since the energy chirp along the electron bunch makes the head to have lower energy, the R_{56} in the seeded undulator will compress the bunch, so lead to a blue shift of the FEL wavelength along the undulator.

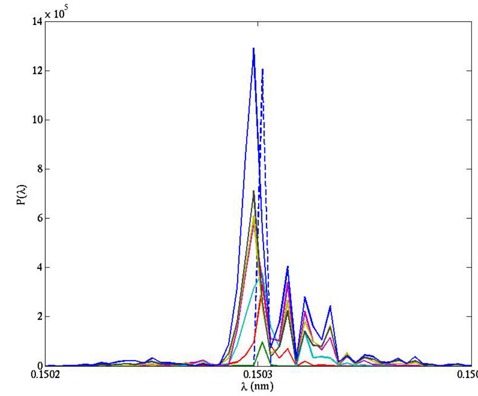

Figure 13: Compression in the undulator leading to a blue-shift of the FEL wavelength along the undulator.

Due to the fact that the RF jitter will change the current profile of the electron bunch, the head-horn will jitter so to cause a jitter in the wakefield effect in the undulator. The above mentioned shift of the FEL wavelength along the undulator is then fluctuating from shot-to-shot.

CONCLUSIONS

In this paper, we identify a few jitter sources which can cause the intensity or frequency shift of a seeded FEL. Some of the jitter sources are common to any accelerator or FEL configuration; some are unique to a seeded FEL or a self-seeding FEL.

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