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Electron Beam Acceleration and Compression for Short Wavelength FELs

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Abstract

A single pass UV or X-ray FEL will require a low emittance electron beam with high peak current and relatively high beam energy, a few hundred MeV to many GeV. To achieve the necessary peak current and beam energy, the beams must be bunch compressed and they must be accelerated in long transport lines where dispersive and wakefield emittance dilutions are important. In this paper, we will describe the sources and significance of the dilutions during acceleration, bunch compression, and transport through the undulator. In addition, we will discuss sources of jitter, especially effects arising from the bunch compressions, and the possible cancellation techniques.

1 Introduction

Recently, a number of single pass UV and X-ray FELs have been proposed [1–4]. These short wavelength FELs impose severe requirements on the electron beams. In this paper, we attempt to survey the issues associated with accelerating and bunch compressing a low emittance beam for a single pass UV or X-ray FEL. Much of this discussion will be based on the parameters for the LCLS which are listed in Table 1 [4]. Of the short wavelength single pass FELs presently being discussed, the LCLS has the most severe beam requirements. Although the issues are the same in other designs, the parameters are different and, in general, the tolerances and problems are easier.

In a single pass FEL, the scale of the beam requirements can be determined from the FEL resonance condition, the dimensionless FEL parameter ρ [5], and the diffraction relation:

$$\lambda_r \sim \frac{\lambda_w}{\gamma^2} \qquad \sigma_{\Delta E/E} \lesssim \rho \qquad \lambda_r \sim 4\pi\frac{\gamma\epsilon}{\gamma} \quad , \tag{1}$$

where λ_r and λ_w are the radiation wavelength and wiggler period, and $\sigma_{\Delta E/E}$ and $\gamma\epsilon$ are the relative energy spread in the beam and the normalized transverse beam emittance; see Ref. 6 for a more detailed discussion of these relations.

Maintaining these three criteria at short wavelengths requires (1) high beam energies, (2) small energy spreads, and (3) small transverse emittances. First, accelerating the beam to high energy is certainly possible, although the accelerators are not inexpensive. Second, from an RF gun, the energy spread criteria is usually easily achieved and thus, to maximize the gain in the FEL, the electron beam needs to be compressed. Compression increases both the peak current, and because the longitudinal emittance is conserved, the energy spread. The optimal degree of compression balances the increase in peak current against the increase in the beam energy spread; because the longitudinal emittance from the RF guns is very small, this optimum is typically attained with kilo-amperes of beam current. Finally, the beam emittance needs to be preserved while the beams are accelerated to high energy and compressed. At this time, RF guns are delivering very small emittances, less than 2 mm-mrad [7], and it is expected that emittances slightly less than 1 mm-mrad will be attained in the near future [8] but these emittances need to be delivered to the FEL undulator.

Table 1 0.45 nm LCLS Beam Parameters

Energy	15 GeV
Peak current	5 kA
$\gamma\epsilon_{x,y}$	1 mm-mrad
Charge	1 nC
σ_z	15 μm
$\sigma_{\Delta E/E}$	2×10^{-4}

In the next sections, we will discuss dilutions of the transverse and longitudinal phase spaces and we will outline the present state of the LCLS design. But, before beginning, it is worth clarifying the difference between the "slice" emittance and the projected beam emittance. In these single pass devices, the emittance and energy spread requirements for *lasing* only need be maintained over a distance λ_r/ρ, sometimes referred to as the cooperation length. This is typically much smaller than the bunch length. For example, in the LCLS, the cooperation length is less than 1 μm while the rms bunch length is roughly 15 μm. Of course, for general operation, the requirements on emittance and energy deviation should be maintained over the entire bunch. For example, an energy deviation correlated with the longitudinal position in the bunch z will cause the FEL output to chirp. Similarly, a wakefield tail, where the transverse centroid of the bunch is correlated with the longitudinal position within the bunch will cause the generated laser to steer as a function of distance along the bunch. Furthermore, if the betatron wavelength is short compared to the FEL undulator length, some slices will perform betatron oscillations through the undulator, decreasing the gain of the FEL.

2 Transverse Phase Space

The principal sources of transverse emittance dilution are: (1) focusing mismatches and transverse coupling, (2) dispersive and chromatic errors, (3) transverse wakefields and RF deflections, and (4) space charge forces. We will discuss each of these sources briefly and then we will describe some emittance correction techniques. Next, we will discuss transverse beam jitter, and finally, we will describe the tolerances in the LCLS design. A more detailed discussion of the sources of emittance dilution and emittance correction techniques can be found in Ref. [9] and references within.

2.1 Focusing Mismatches

Mismatches of the focusing system and transverse emittance (betatron) coupling can lead to an effective emittance increase after the mismatches filament (phase mix). The focusing mismatches arise from errors in the quadrupole placement and strengths while the betatron coupling is primarily introduced by rotation alignment errors of the quadrupoles. With equal x and y emittances, the betatron coupling effects are not very significant and the alignment tolerance on the quadrupoles is a few mrad, but, care is needed in the optics design to avoid unwarranted sensitivity to focusing errors. Finally, both of these are multiplicative emittance dilutions and thus the tolerances do not become more severe as the beam emittance is decreased.

2.2 Dispersive and Chromatic Effects

Dispersive effects refer to the dependence of the trajectory on energy which arise when the trajectory is deflected and chromatic effects refer to the dependence of the transverse focusing on energy. Because the beam has an energy spread, these effects can lead to emittance dilution; particles with different energies have different trajectories or are focussed differently. Specifically, dispersive errors arise from injected trajectory errors or misalignments of the Beam Position Monitors (BPMs) which cause the corrected trajectory to be deflected from side-to-side. Chromatic effects arise from limitations of the energy bandwidth of the focusing channel and need to be considered in the optics design.

Both of these effects are proportional to the energy deviation or spread. In linacs for FELs, the "uncorrelated" energy spread, *i.e.* the energy spread of a slice at some position within the bunch, is usually much less than the "correlated" energy deviation which arises from the accelerating RF and the longitudinal wakefields. Thus, the tolerances to limit the emittance dilution of the *beam* are more severe that the tolerances to limit the dilutions over a cooperation length. For example, in the LCLS design, the uncorrelated energy spread is very small $\sigma_{\Delta E/E} \lesssim 10^{-3}$ while, at some locations, the correlated energy spread approaches 2%. Finally, although the alignment tolerances can be severe, it is possible to use the beam to diagnose the quadrupole and BPM offsets. Presently, beam-based alignment is used in the SLAC linac to align the quadrupoles and BPMs with an rms error of roughly $80\,\mu$m [10].

2.3 Transverse Wakefields and RF Deflections

Transverse wakefields arise from offsets of the beam in the accelerating structures. The offsets may result from injected trajectory errors, misalignments of the BPMs, or misalignments of the structures. Wakefields dilutions also occur at beam collimators or in small aperture vacuum chambers. The wakefields deflect the tail of the beam, correlating the transverse phase space with the longitudinal position within the bunch. RF deflections arise from asymmetries in the input and output couplers on the accelerating structures, structure fabrication errors, and angular orbit errors through the structures. Like transverse wakefields, the RF deflections correlate the transverse phase space with the longitudinal position within the bunch. Finally, both of these dilutions are proportional to the bunch length and can be minimized by compressing the bunch at relatively low energies.

Unfortunately, it can be more difficult to accurately align the accelerating structures than the quadrupoles. As mentioned, quadrupole alignment errors can be accurately determined from the beam deflections, but these are much smaller in the accelerating structures. One possible alignment technique is to directly measure the induced dipole mode in the structure; accurate alignment is thought to be attainable with this technique although it has not been demonstrated.

2.4 Space Charge Forces

Space charge forces impose a severe limitation on the transverse emittance and the peak current. There are two regimes that are important: first, forces that arise during straight-line motion, and second, forces that arise in bending magnet systems. In the first case, the force scales linearly with local beam current and inversely with the square of the beam energy (I/γ^2). The established solution to this problem is to have a relatively low current from the RF gun, accelerate the beam rapidly, and use emittance compensation [11]. The beam can then be compressed to high peak currents at much higher energy where the forces are not so important. Both experimental results and computer codes, such as PARMELA, show that emittances less than 2 mm-mrad are attainable in this manner [7].

In the second regime, namely in the bending magnets of a bunch compressor, there are space charge forces that do not scale as $1/\gamma^2$. Calculations for DC beams [12] and simple geometric arguments would suggest that these forces scale as the square of the beam size divided by the square of the bending radius $(\sigma_x/\rho)^2$. More detailed calculations for bunched beams [13] indicate that the forces scale as $(\sigma_x/\rho)^{3/2}$. This effect can be important when bunch compressing low emittance beams. For a bunch with a 1 mm radius and 1 kA of current in a vacuum chamber with a 1 cm radius, the expected emittance growth is 10 mm-mrad per radian of bend; this dilution decreases rapidly with decreasing beam radius and can be made negligible by properly designing the bunch compressors.

2.5 Emittance Correction

All of the sources described are conservative dilutions: the beam emittance is not actually increased, instead the various degrees of freedom become correlated, leading to an increase in the projected emittance. Because the dilutions are conservative, they can be corrected provided that the correlations have not filamented (phase mixed). Emittance correction of the low energy space charge forces is now a well established technique for RF guns [11]. In the same manner, emittance correction of wakefield and dispersive dilutions is a standard technique in high energy linacs. Presently, emittance correction bumps are used to reduce dilutions in the SLC linac from over 300% to less than 50% [14]. Of course these emittance correction techniques rely on highly accurate diagnostics that can measure the beam centroid and emittance.

2.6 Transverse Jitter

Transverse position jitter can arise from variations in the laser spot on the RF gun photocathode, transverse vibration of the quadrupole magnets, or magnet power supply fluctuations. The jitter has three effects: (1) it leads to transverse emittance growth due to wakefields and dispersive effects, (2) it makes tuning of the transverse phase space difficult, and (3) it shifts the position of the beam centroid, causing variations in the FEL output.

The amplification of jitter by the transverse wakefields can be reduced using BNS damping [15] where an energy deviation, correlated with the position within the bunch z, is used to compensated the effect of the wakefields. In addition, low frequency jitter ($f \lesssim f_{rep}/30$) and slow drifts can be reduced with beam-based feedbacks. But, the tolerance on the high frequency jitter is still a fraction of the beam size and, as the beam emittance decreases, the tolerances can become severe. Furthermore, it is difficult to eliminate all sources of jitter by design and additional sources can appear due to subtle hardware failures. Thus, it is important to have diagnostics to detect and isolate the sources of jitter that may appear.

2.7 Tolerances in the LCLS

In the LCLS design, we plan to make use of many of the alignment and emittance correction techniques developed for the SLC. Thus, we have assumed random misalignments of the quadrupoles and BPMs with an rms of $100\,\mu$m and random misalignments of the accelerating structures having an rms of $300\,\mu$m; these are slightly larger than those thought to exist in the SLC linac. We also assumed that the beam trajectory is steered reproducibly to the BPMs with an error less than $15\,\mu$m. In simulations using these errors, wakefields and anomalous dispersion dilute the emittances by 65%, on average, which can then be corrected with emittance correction techniques to roughly 20% dilution. Finally, quadrupole power supply fluctuations at the level of 5×10^{-4} or random quadrupole vibration at the level of 140 nm will cause the beam centroid to jitter by 10% of the rms beam size; other tolerances were not found to be significant.

3 Longitudinal Phase Space

At this point, we can discuss the longitudinal phase space. As mentioned, in a short wavelength FEL, the bunch from the RF gun needs to be compressed to achieve maximum gain. The bunch compression is performed by introducing an energy deviation δ, correlated with the longitudinal position z in the bunch, and then passing the bunch through a magnetic system where the path length is energy dependent. When designing the compressions and the transport of the longitudinal phase space, there are four issues that we need to consider: (1) attaining desired the high peak currents, (2) removing any correlated energy deviation which chirps the FEL, (3) making the system insensitive to timing or intensity jitter from the RF gun laser, and (4) transverse phase space issues, *i.e.* space charge, transverse wakefields, *etc.* as described in the previous section.

3.1 High Peak Current

To optimize the gain in a short wavelength FEL, we need very high peak currents. These currents are attained by compressing the bunch length at relatively high energy so that transverse and longitudinal space charge effects are not significant. Ideally, the longitudinal phase space in a bunch compressor is conserved. Unfortunately, the curvature of the RF waveform, the longitudinal space charge forces, and the longitudinal wakefields, introduce δ-z correlations that are not linear. Because it is hard to compensate for these nonlinearities in the magnet systems, this dilutes the effective longitudinal emittance and reduces the amount of bunch compression that can be performed. To avoid this, we usually add large correlations by running far from the RF crest and then only partially compressing the bunch — the residual correlated energy spread is removed later with either the RF or the induced longitudinal wakefields. This has the added benefit of requiring a smaller path length change per unit energy deviation, making the magnetic compressor system simpler.

When partially compressing the bunch, one can either "under-compress" or "over-compress" the bunch. In the former, the longitudinal phase space is rotated by less than 90° and in the later the phase space is rotated past the minimum bunch length. In some instances it can be advantageous to over-compress the bunch [16], but, when the longitudinal emittance is very small, over-compressing exacerbates space charge problems and thus is not usually applicable for short wavelength FEL drivers.

3.2 Small Energy Deviation

With high energy short bunches, the primary sources of correlated energy deviation are the longitudinal wakefields and the accelerating RF. The wakefield effects are usually corrected by accelerating the beam ahead of the RF crest [1]. Unfortunately, as the bunches become very short, this technique is no longer effective. For example, in the SLAC linac, with an accelerating

[1] An additional approach that might prove useful is to shape the longitudinal profile of the bunch to reduce the effect of the longitudinal wakefields [17,16].

gradient of 17 MV/m, the shortest bunch where the RF can be used to compensate for the longitudinal wakefield is roughly 100 μm.

Thus, to achieve very short bunches with small correlated energy spreads one has to either (1) accelerate a longer bunch and then fully compress it at the end of the linac, or, (2) one can add a large correlated energy deviation, before the bunch is fully compressed, that the longitudinal wakefield removes during the subsequent acceleration. In the LCLS design, we use the later technique since, as mentioned earlier, it is difficult to fully compress the bunch.

Finally, the restive wall wakefield in the undulator will also lead to a correlated energy deviation [18]. For proper operation of the FEL, the induced energy deviation should be much less than the desired bandwidth. For example, if we assume an aluminum undulator vacuum chamber with a 3 mm radius and the LCLS parameters of 1 nC charge, a 15 μm rms bunch length, and a 40 m undulator, we find an induced peak-to-peak energy deviation along the bunch of roughly 20 MeV; this scales inversely with the vacuum chamber radius.

3.3 Longitudinal Jitter

When designing the transport and compression sections, we need to consider effects of phase and intensity jitter from the RF gun laser; this is usually a more severe limitation than the RF timing. Both of these effects will change the δ-z correlation. In the case of phase jitter, the δ-z correlation varies because of the non-linearity of the RF while the variation occurs with intensity jitter because a more intense bunch generates larger wakefields. When the δ-z correlation changes, the rotation of the longitudinal phase space changes and the compressed bunch length and peak current vary.

Assuming that the longitudinal emittance is extremely small, we can neglect the uncorrelated energy spread and calculate the dependence of the bunch length on the phase jitter $\Delta\phi$ after a single compression [19]:

$$\frac{1}{\sigma_z^\star}\frac{d\sigma_z}{d\Delta\phi} = \frac{\sigma_{z0}^\star}{\sigma_z^\star}\left[\left(\frac{\sigma_z^\star}{\sigma_{z0}^\star} \pm 1\right)\cot\phi\right] \quad , \tag{2}$$

where $\sigma_{z0}^\star$ and $\sigma_z^\star$ are the nominal initial and final bunch lengths, ϕ is the nominal RF phase, and the negative sign corresponds to under-compressing while the positive sign is for over-compressing. Notice that the sensitivity depends upon the compression factor σ_{z0}/σ_z.

At this point, we can perform a similar calculation to include the effect of a second compression and we find two terms in the expression that can be chosen to cancel. For example, if the compression in the LCLS were performed in a single stage, injection phase errors of 60 fs would lead to 10% variation of the peak current. Instead, with two stages, we have an injection phase tolerance of 1 ps for 10% variation of the beam current; the jitter tolerance is eased by a factor of roughly 16.

3.4 LCLS Design

As just described, we need two bunch compressors in the LCLS to reduce the sensitivity to incoming phase and intensity jitter. The first compressor is located at the beginning of the linac at an energy sufficiently high so that space charge effects are negligible (150 MeV). It compresses the bunch by a factor of three to an rms bunch length of roughly $400\,\mu$m which decreases the emittance dilution due to the transverse wakefields while, in the SLAC linac, still allowing the correlated energy deviation to be manipulated with the accelerating RF. The second compressor is located at 7 GeV and compresses the bunch to it final rms length of $15\,\mu$m. With a bunch this short, the accelerating RF cannot significantly modify the energy deviation within the bunch. Thus, the correlated energy deviation before the compressor and the compressor R_{56} are adjusted so that, after the compression, the bunch has a correlated energy deviation that is removed by the longitudinal wakefields during the subsequent acceleration.

4 Summary

We have attempted to describe the relevant dynamics in the transverse and longitudinal phase spaces during the acceleration and compression of a beam for a short wavelength FEL. We have not touched on the diagnostics or controls requirements which will be exceedingly important for these accelerators. In particular, as the tolerances become tight, one must design the system so that it can be dynamically tuned while the required stability is maintained through fast beam-based feedbacks.

We have also briefly described the present state of the LCLS design. The LCLS beam transport has been designed using computer codes, such as PARMELA and those used to design future linear colliders, that have been bench-marked against experimental results and thus, for reasonable extrapolations of the present experimental parameters, there is confidence in the predictions. The principal uncertainty in the design are some issues related to the bunch compressions (space charge and effects of the beam distribution) and some of the SASE FEL physics (startup from noise, saturation, *etc.*). Fortunately, these issues will be experimentally verified in the next few years [3].

Finally, it is worth noting that many of the emittance preservation requirements for the LCLS are being demonstrated at SLAC routinely. Figure 1 is a plot of the normalized vertical emittance at the beginning (a) and end of the 3 km SLAC linac (b) during a five day run of the Final Focus Test Beam (FFTB) [20]. The beam, with 1 nC of charge, is generated in the SLC damping ring which operates far from the coupling resonance so $\gamma\epsilon_y \sim 1.5$ mm-mrad while $\gamma\epsilon_x \sim 30$ mm-mrad. The bunch is then compressed from an rms bunch length of 6 mm to $500\,\mu$m at which point it is injected into the SLAC linac and accelerated. The vertical emittance dilution is routinely less than 50%; simulations predict even less emittance growth in the LCLS design than in the FFTB experiment.

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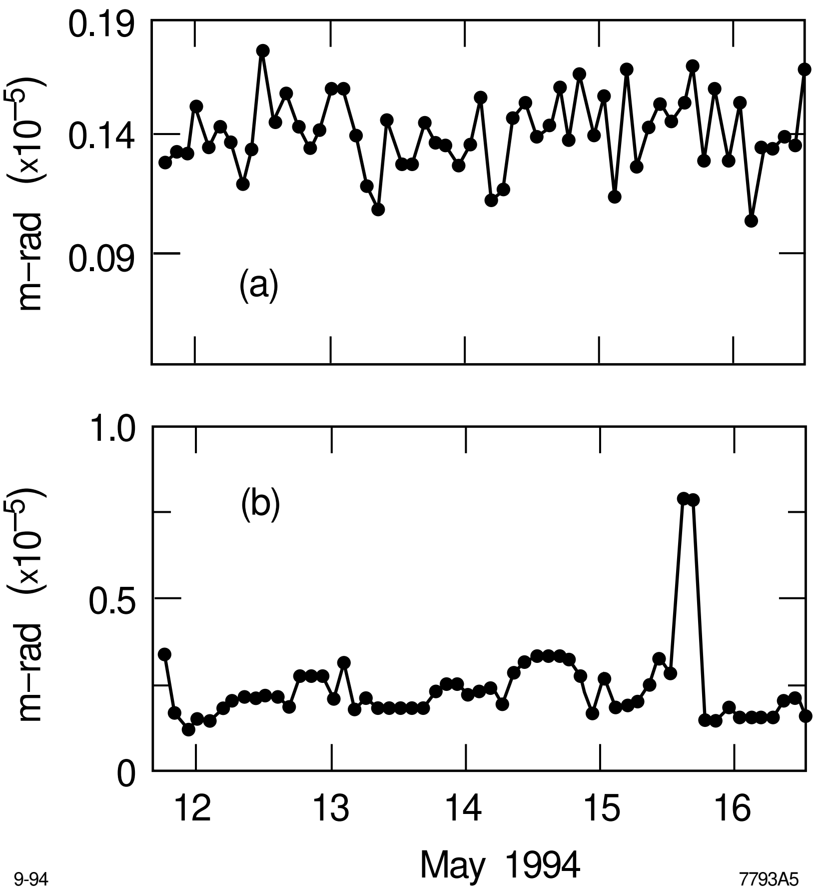
5 Figures

Figure 1. Vertical emittance at the beginning (a) and end (b) of the SLAC linac during the FFTB experimental program.


0.19
0.14
0.09
m−rad (x10^{-5})
(a)
1.0
0.5
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m−rad (x10^{-5})
(b)
12
13
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Fig. 1