Chirping the LCLS Electron Beam

P. Emma

SLAC

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Abstract

We explore scenarios for generating a linear time-correlated energy spread in the LCLS electron bunch, prior to the undulator, that is needed for optical (x-ray) pulse compression. The correlated energy spread ('chirp') is formed by generating an energy gradient along the length of the electron bunch using RF phasing and/or longitudinal wakefields of the accelerating structures. The sign of the correlation is an important limitation. Excluding a complete re-design of the compression systems, the best possibility is to use 'over-compression' to effect the required energy chirp. This is easily done with only a slight strength increase ($\sim 10\%$) in the chicane bends of the second compressor. In this case, the bend-plane emittance dilution associated with the increased coherent synchrotron radiation (CSR) in the bunch compressor may, however, *significantly compromise the electron beam density*. The CSR calculations for the momentary extremely short ($\sim 1\ \mu\text{m}$) electron bunch during over-compression are quite subtle and an adequate confidence level may not be achievable. A practical limit in this short-pulse scenario may be to use spontaneous rather than FEL radiation. Ignoring the potential emittance growth, a FWHM electron energy spread of 2 % is possible.

1 Introduction

The nominal LCLS accelerator design [1] provides a very narrow electron energy spread at 14 GeV of $<0.03\%$ rms. This is achieved by using the strong longitudinal geometric wakefields of the micro-bunch in the linac S-band accelerating structures to cancel the linearly correlated energy spread of the second bunch compressor chicanes (BC2). Fig. 1 shows the *nominal* [1] energy-time (also referred to as δ - z) correlation (see lower right plot) immediately after the BC2 chicane at 4.5 GeV [2]. After this point the beam is accelerated to 14.3 GeV through 560 meters of RF structures (*i.e.* the L3-linac). At 1-nC of charge, and with the very short 24- μm rms bunch length, a strong wakefield is generated in these structures where the head of the bunch loads the tail. This loading is very nearly linear (for a uniform temporal distribution as in Fig. 1) and has been arranged to fully cancel the correlated energy spread. Fig. 2 shows the same plots as in Fig. 1, but now taken at 14.3 GeV, after the full L3-linac. The linear *relative* energy spread has been reduced by the energy increase, and then virtually removed by the L3 wakefield.

Fig. 1. Nominal e^- bunch temporal distribution (top-left), energy distribution (top-right) and longitudinal phase space (lower-right) at 4.5 GeV immediately after the BC2 chicanes and prior to the L3-linac (bunch head at left toward $z < 0$). The rms energy spread at the BC2 exit, prior to the L3-linac, is 0.9 %.

Fig. 2. Same *nominal* e^- plots as in Fig. 1, but taken at 14.3 GeV, after the L3-linac (*i.e.* just prior to the undulator). The non-linearity in the δ - z correlation is mostly due to the resistive-wall wakefields in the linac and pre-undulator transport lines. The rms energy spread is 0.028 % at 14.3 GeV.

Note that the linear correlation at BC2 (in Fig. 1) is introduced by off-crest RF phasing ($\sim 40^\circ$) in the L2-linac before BC2. The positive sign in the Fig. 1 correlation ($\langle z\delta \rangle > 0$, with bunch head toward $z < 0$) is required so that the bunch length is *compressed* (rather than expanded) in the BC2 chicanes. This sign cannot be arbitrarily reversed unless a more complicated compressor design (that includes quadrupole magnets) is substituted for the chicanes. This means that for a chicane-type compressor (desired for its simplicity and adjustability) the wakefield in the L3-linac always generates a correlation which is opposite in sign to the correlation needed for bunch compression. This cancellation greatly aids in the *nominal* machine design, but also makes it difficult to provide more than ~ 0.1 % rms linear energy spread ('chirp') by re-phasing the L2-linac. Moving farther off-crest quickly reduces the L2-linac energy gain, without generating a significant energy chirp. Moving closer to RF crest generates more compression-limiting RF non-linearity and also forces a stronger chicane, which risks significant bend-plane emittance dilution due to coherent synchrotron radiation (CSR), again with only a minor energy chirp generated.

Similarly, generating a chirp by off-crest phasing in the L3-linac is not practical. This is due to the very short bunch in L3 ($24\text{-}\mu\text{m}$ rms) and the relatively long RF wavelength in the SLAC linac ($\lambda \approx 10.5$ cm). The rms relative energy spread, σ_δ , generated by an off-crest accelerating voltage of $V = GL$, for an rms bunch length of σ_z is given by

$$\sigma_\delta \approx \frac{2\pi\sigma_z}{\lambda E_f} GL \sin \varphi , \quad (1)$$

where E_f is the final beam energy (~ 14 GeV), G is the accelerating gradient (~ 19 MV/m), L is the linac length (~ 560 m), and φ is the RF phase ($\varphi = 0$: on-crest). Even for a 45° RF phase (which would mean the L3-linac accelerating gradient would somehow need to be increased by $\sqrt{2}$ in order still to achieve 14 GeV) a $24\text{-}\mu\text{m}$ rms bunch will only generate 0.08 % rms energy spread at 14 GeV. Therefore, generating a significant chirp in the S-band L3-linac using only RF phasing is impossible.

2 Over-Compression

Excluding a complete re-design of the compression systems, this leaves one possibility: ‘over-compression’. Bunch compression in BC2 is nominally configured as ‘under-compression’. This is the condition when the ‘rotation’ in longitudinal phase space is less than $\pi/2$. In this case a positive $\langle z\delta \rangle$ correlation prior to the chicane remains positive after the chicane. This is a desirable configuration since it requires a weaker chicane than does over-compression and, more importantly, does not cross over the $\pi/2$ rotation point somewhere inside the chicane. This cross-over point (*i.e.* ‘optimal-compression’) is associated with an extremely short bunch of just a few microns in the case of the LCLS. If this point occurs in the middle of a bending system, the strong CSR and potential wakefields of the very short bunch might be very damaging to the bend-plane emittance. If these effects are not too severe [3], however, over-compression offers much greater potential for generating significant electron chirp prior to the undulator.

Ignoring the emittance growth effects described above, over-compression of the LCLS bunch in BC2 is quite easy. If the nominal BC2 chicane dipole fields are simply increased 9.5 %, the bunch will over-compress, as shown in Fig. 3, with a final negative $\langle z\delta \rangle$ correlation immediately after the chicanes. This arrangement produces nearly the same bunch length [4] as does under-compression in Fig. 1, yet with a negative $\langle z\delta \rangle$ correlation. The acceleration in the L3-linac to 14 GeV will now generate nearly the same wakefield as before, which will now *add* to the net $\langle z\delta \rangle$ correlation, making it even more negative. Fig. 4 shows the same plots as in Fig. 2, but now calculated for the case of over-compression. In this case, the rms energy spread is 0.55 % at 14.3 GeV and has a negative, and nearly linear, $\langle z\delta \rangle$ correlation. The full-width energy spread is almost 2 % and the rms bunch length, after the DL2-bend system, is back to the nominal value of $24\text{ }\mu\text{m}$. The bunch charge remains at 1 nC. This figure shows that the leading electrons (the bunch head at $z < 0$) are now at higher energy than the trailing electrons (the bunch tail at $z > 0$). This correlation should generate an accompanying optical chirp that might be used to compress the x-ray pulse to below 50 fsec. This level of chirp (~ 2 % FWHM) cannot be generated with a positive $\langle z\delta \rangle$ correlation (*i.e.* using under-compression).

Fig. 3. Same plots as in Fig. 1 (at 4.5 GeV just after the BC2 chicanes and prior to the L3-linac), but with the BC2 chicane dipole fields increased 9.5 % to over-compress the bunch (bunch head at left toward $z < 0$). The final $\langle z\delta \rangle$ correlation (lower-right) is now negative, but with the same nominal 0.9 % rms energy spread.

Fig. 4. Same plots as in Fig. 2 (at 14 GeV, after the L3-linac and just prior to the undulator), but shown for over-compression. In this case, the rms energy spread is 0.55 % at 14.3 GeV and has a negative, and nearly linear, $\langle z\delta \rangle$ correlation. The full-width energy spread is nearly 2 % (the bunch head energy is higher than the tail) and the rms bunch length, after the DL2-bend system, is 23 μm .

3 Alternate Method

Another method to reduce the length of the x-ray pulse might be implemented by a combination of more electron compression and some final added optical compression. In this scenario the L2-linac RF phase is moved closer to crest (by $1-2^\circ$) and the BC2 chicane magnets are increased in field (by $\sim 5\%$), still using under-compression. The wakefield induced energy spread of the L3-linac then dominates the final energy spread because of the shorter bunch in L3 (stronger wakefield) and because of the reduced initial energy spread from the re-phased L2-linac. If the bunch is compressed to $10\ \mu\text{m}$ (rather than the nominal $24\ \mu\text{m}$) the final correlated energy spread will be $\sim 0.35\%$ FWHM. This is quite small, and it is limited again by CSR effects in the compressors and wakefield effects in the undulator, but the combination of compression improvements might be a practical alternative. Since here the electron bunch does not pass through the singularity point of optimal compression, the effects of CSR might be more confidently predicted and the double chicane can be re-optimized to mostly maintain the cancellation of the CSR-induced emittance dilution. The RF phase stability tolerances will, however, be even tighter here ($<0.1^\circ$ S-band).

4 Conclusions

The nominal LCLS accelerator design uses RF phasing, under-compression and longitudinal wakefields of the accelerating structures to cancel the final correlated energy spread (chirp) in the electron bunch to $<0.03\%$ rms. The wakefield cancellation and the very short bunch in the final L3-linac make it difficult to generate a chirp larger than $0.1-0.2\%$ rms without switching to an over-compression configuration, which risks potentially damaging emittance growth. If this emittance growth is tolerable [3], the present accelerator design can be operationally tuned, by adjusting the BC2 dipole fields, to over-compress the electron bunch to the same peak currents as in the nominal case of under-compression. Over-compression has the advantage of producing an energy gradient (correlation) along the bunch with a sign that then *adds* to the strong wakefield of the final L3-linac, rather than cancels, as in the nominal design. In this case an rms energy spread of 0.55% (FWHM of almost 2%) can be generated at 14 GeV and the head of the bunch is higher energy than the tail (see Fig. 4). Calculations that examine the chromatic emittance dilution in the L3-linac and the DL2-bend system, given the increased energy spread, remain to be done. Finally, the CSR-induced emittance growth in the BC2 chicanes may not be controllable. In fact, the over-compression scenario destroys the planned CSR emittance-growth cancellation of the double-chicane system [5]. **The potential emittance dilution may make this chirp scenario impractical for FEL radiation**, but it may still be a possible short-pulse scheme using spontaneous radiation.

5 References

- [1] “LCLS Design Study Report”, SLAC-R-521, April 1998.
- [2] The nominal compression parameters have been modified with respect to reference [1]. The parameters used in this note are those described in LCLS-TN-99-3 (page-3, Table-1), May 3, 1999.
- [3] Detailed and non-trivial calculations need to be done to verify the severity of the effects. Even so, the effects in this 1- μm bunch length regime are quite subtle, and calculations with a satisfactory confidence level may not be achievable.
- [4] The bunch length just after BC2, for the case of over-compression, has been set slightly larger than for under-compression (30 μm versus 24 μm) because the large chirp at 14 GeV instigates an slight additional compression of 6 μm in the DL2-bend system which resides immediately upstream of the undulator.
- [5] P. Emma and R. Brinkmann, “Emittance Dilution Through Coherent Energy Spread Generation in Bending Systems”, *Proceedings of the 1997 IEEE Particle Accelerator Conference*, Vancouver, BC, Canada, 1997.