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LCLS Accelerator Parameters and Tolerances for Low Charge Operations

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1 Introduction

An option to control the X-ray FEL output power of the LCLS [1] by reducing the charge of the electron bunch has been proposed [2]. This option brings about some interesting changes to the LCLS accelerator parameters which significantly ease many of the most challenging tolerances. In this note we re-optimize the acceleration and bunch compression systems to accommodate an electron bunch charge of 0.1 nC rather than the nominal 1 nC. The accelerator parameter changes are applied in an 'operational' sense so that they may be utilized after the high-charge LCLS design has been constructed. Thus the low-charge option is consistent with the nominal LCLS hardware configuration, with the exception that some electron beam diagnostics may require upgrading. In what follows we emphasize the favorable impact on phase space dilution effects at low charge rather than the ability to control the FEL output power. Operating the LCLS along a line from 0.1 to 1.0 nC will provide the flexibility to respond to charge dependent problems.

2 Injector Scaling

Reference 2 refers to the approximate rms emittance and bunch length scaling with bunch charge, Q, for a 1.6-cell S-band photoinjector [3]. These results are listed below.

$$\gamma\varepsilon_{x,y} \approx (1.45\ \mu\text{m})\cdot\sqrt{0.38\cdot Q\,[\text{nC}]^{4/3} + 0.095\cdot Q\,[\text{nC}]^{8/3}} \tag{1}$$

$$\sigma_z \approx (0.63\ \text{mm})\cdot Q\,[\text{nC}]^{1/3} \tag{2}$$

The bunch charge is in units of nC, the normalized emittance in μm, and the rms bunch length in mm. The approach described in reference 2 uses the above scaling relations and maintains a constant saturation length (fixed length undulator) and a constant intrinsic electron energy spread (0.02 % rms). At a bunch charge of 0.1 nC FEL saturation is then achieved with a final bunch length which is virtually unchanged from the LCLS reference design (24 μm rms). The FEL output power is reduced by an order of magnitude by using a peak electron bunch current of just 350 A. With the shorter bunch from the injector as described in Eq. (2) and an unchanged final bunch length, the overall compression factor required is reduced by approximately a factor of two.

In order to reach saturation in 94 meters at 0.1 nC a normalized rms emittance of $\gamma\varepsilon_{x,y} \approx$ 0.2 μm and an initial rms bunch length of ~300 μm are used [Eqs. (1) and (2)]. These are very optimistic injector results which need experimental verification. The validity of the photoinjector scaling is not discussed further here. The remainder of this note explores the impact of such operations on the parameters and tolerances of the accelerator and undulator systems.

3 Accelerator System Parameter Adjustments

3.1 High-Charge Parameters

Since the publication of reference 1, several preliminary modifications have been made to the bunch compression parameters which help reduce pulse-to-pulse jitter sensitivities. Before we describe the low-charge parameters we first list these new high-charge parameters in Table 1. This will be considered the high-charge (1-nC) reference design.

These changes, with respect to reference 1 (see Table 7.2-1), are primarily due to a shorter expected bunch from the injector [4] and the relocation of the second bunch compressor double-chicane (BC2) from 6.0 GeV to 4.54 GeV in order to reduce the effects of synchrotron radiation and pulse-to-pulse jitter.

Table 1. LCLS high-charge (1-nC) bunch compression and acceleration parameters per beamline section. These parameters are an update since the publication of reference 1 (see Table 7.2-1).

Beamline	E_{in}	E_{out}	$\sigma_{z\text{-in}}$	$\sigma_{z\text{-out}}$	$\sigma_{\delta\text{-in}}$	$\sigma_{\delta\text{-out}}$	φ_{rf}	R_{56}
	GeV	GeV	mm	mm	%	%	deg	mm
Linac-1	0.15	0.25	0.72	0.72	0.1	1.3	41	—
BC1	0.25	0.25	0.72	0.29	1.3	1.3	—	31.0
Linac-2	0.25	4.54	0.29	0.29	1.3	0.9	35	—
BC2	4.54	4.54	0.29	0.02	0.9	0.9	—	29.4
Linac-3	4.54	14.4	0.02	0.02	0.9	0.03	0	—

3.2 Low-Charge Parameters

Qualitative Overview

As shown in reference 1, the correlated energy spread (chirp) of the electron bunch introduced for compression in BC2 is nominally removed by the strong geometric wakefield of the final linac (linac-3). The wakefield is charge dependent and therefore a lower charge will necessitate a reduced level of BC2 chirp (*i.e.* the RF accelerating phase in linac-2 needs to be set closer to crest for low charge operations). It may seem more difficult to compress the bunch to the same length in BC2 with less RF-induced chirp since the momentum compaction, R_{56}, of the chicane then needs to be increased (coherent radiation effects in the chicane increase rapidly with $|R_{56}|$). The situation is, however, mitigated by the lower charge and the shorter bunch length from the injector [see Eq. (2)].

The extremely small emittance (0.2 μm) in the linac may also seem difficult to preserve in the presence of transverse wakefields, misaligned quadrupole magnets and coherent synchrotron radiation (CSR) in the chicanes. Again, however, in all cases the lower charge and/or reduced bunch length prior to BC2 eases these tolerances to levels comparable to or significantly easier than the LCLS high-charge design.

In addition to the relaxation of accelerator tolerances, other potentially damaging effects such as resistive-wall and surface roughness wakefields of the undulator vacuum chamber are greatly reduced. Some quantitative results follow.

Parameter Adjustments

In order to study the impact of a reduced bunch charge on accelerator systems the compression parameters of Table 1 are roughly re-optimized using the computer program *LiTrack* [5] which includes the effects of longitudinal wakefields, the sinusoidal shape of the RF accelerating voltage, and the 1st and 2nd order momentum compaction of the chicanes (R_{56} and T_{566}). The locations and beam energies of the compressors are maintained and only the chicane strengths (e.g. a dipole power supply) and the linac RF phases are adjusted. The intermediate rms bunch length in Linac-2 (0.29 mm in high-charge mode) is now chosen, somewhat arbitrarily, at 0.10 mm. The RF phase in Linac-2 is set to 22˚ (13˚ closer to the 0˚-crest than in high-charge mode) so that a 24 μm rms bunch in Linac-3 at 0.1 nC will produce a net rms relative energy spread at 14.4 GeV of <0.05 %. With these choices, and an injector bunch length of 0.33 mm at 0.1 nC, the remaining parameters are adjusted. The results are listed in Table 2 below which should be compared with the high-charge parameters of Table 1.

Table 2. LCLS low-charge (0.1-nC) bunch compression and acceleration parameters per beamline section. These parameters should be compared to those of Table 1 (changes are in **bold**-type here).

Beamline	E_{in}	E_{out}	$\sigma_{z\text{-in}}$	$\sigma_{z\text{-out}}$	$\sigma_{\delta\text{-in}}$	$\sigma_{\delta\text{-out}}$	φ_{rf}	R_{56}
	GeV	GeV	mm	mm	%	%	deg	mm
Linac-1	0.15	0.25	**0.33**	**0.33**	0.1	**0.6**	41	—
BC1	0.25	0.25	**0.33**	**0.10**	**0.6**	**0.6**	—	**35.0**
Linac-2	0.25	4.54	**0.10**	**0.10**	**0.6**	**0.2**	**22**	—
BC2	4.54	4.54	**0.10**	0.02	**0.2**	**0.2**	—	**34.0**
Linac-3	4.54	14.4	0.02	0.02	**0.2**	**0.04**	0	—

Note that neither the BC1 nor the BC2 chicane strengths (R_{56}) have changed a great deal. Furthermore, the average rms energy spread has been significantly reduced everywhere. This is due to the reduced bunch length and the linac-2 RF phasing closer to crest. The smaller energy spread eases quadrupole alignment tolerances with respect to dispersion generation. In addition, the shorter bunch and lower charge greatly reduce the emittance dilution due to transverse wakefields of misaligned accelerator structures.

Figure 1 shows the final longitudinal phase space at 14.4 GeV for both the 1-nC and the 0.1-nC cases. Temporal and energy distributions are also shown. For the low charge case the energy chirp is quite linear but still more than a factor of two below the 0.1 % rms chirp tolerance. The head of the bunch is at left in the first and third column of plots. A more flattened temporal distribution at 0.1 nC is probably possible with some continued optimization work.

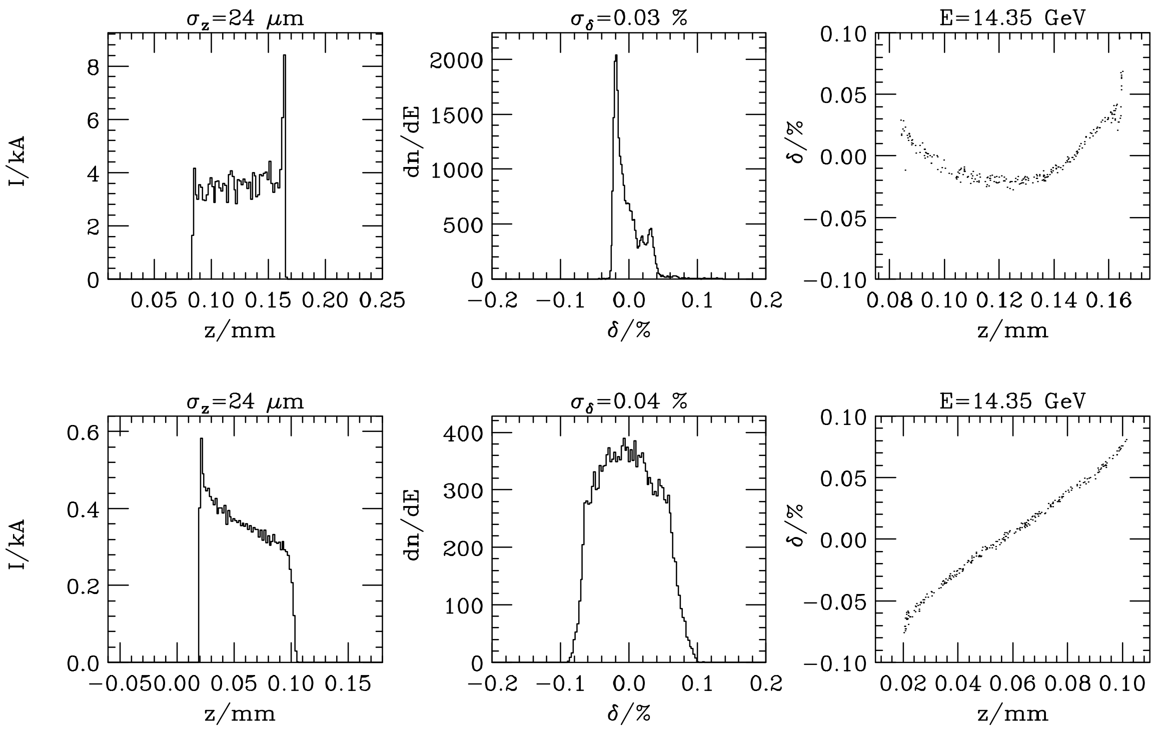

Figure 1. Final longitudinal phase space at 14.35 GeV for both the 1-nC (top row of plots) and 0.1-nC (bottom row) cases. Temporal and energy distributions of the electron bunch are shown at left. For the low charge case the energy chirp is quite linear but still well below the 0.1 % rms chirp tolerance.

Emittance Dilution Effects

As mentioned above, many of the potential emittance dilution effects in the accelerator become less severe with the low-charge parameter set. The following lists several of the most important effects.

Coherent Synchrotron Radiation

The relevant low-charge parameter changes for the BC1 chicane are listed in Table 3 where *Ne* is the total bunch charge.

Table 3. Changes to the CSR-relevant parameters in the BC1 chicane.

Ne	nC	1.0	0.1
R_{56}	mm	31	35
ε_N	μm	1.0	0.2
σ_z	μm	290	100

The scaling of the emittance growth generated by coherent synchrotron radiation in the last dipole of a chicane (where the bunch is typically shortest) can be approximated by

$$\left(\frac{\Delta\varepsilon}{\varepsilon_0}\right)_{\mathrm{CSR}} \sim \frac{N^2\left|R_{56}\right|^{5/3}}{\varepsilon_N\sigma_z^{8/3}}, \tag{3}$$

where N is the bunch population, ε_N is the nominal normalized rms emittance and σ_z is the rms bunch length in the last bend. Applying the relative changes of Table 3 to the scaling in Eq. (3) indicates that the CSR emittance growth in BC1 is a factor of 1.15 stronger at low charge than at high charge, primarily due to the shorter bunch. This is a comparative dilution level (a 15 % increase) which does not present a significant new challenge.

The CSR-relevant low-charge parameter changes for the second compressor (BC2) are listed in Table 4 (the bunch length in the last dipole of BC2 is not changed with charge).

Table 4. Changes to the CSR-relevant parameters in the BC2 system.

Ne	nC	1.0	0.1
R_{56}	mm	29	34
ε_N	μm	1.0	0.2

Applying the relative changes of Table 4 to the scaling in Eq. (3) indicates that the CSR emittance growth in BC2 is just 7% of the high charge case. The CSR effect in BC2 is therefore virtually removed as a dilution mechanism at low charge.

Quadrupole Alignment and Dispersion Effects

A misaligned quadrupole magnet will generate anomalous momentum dispersion which may dilute the emittance. The effect is dependent on the relative energy spread in the quadrupole. The relevant low-charge parameter changes for linac-2 are listed in Table 5 where for simplicity we have used the mean energy spread along the linac.

Table 5. Changes to the relevant alignment parameters in linac-2.

Ne	nC	1.0	0.1
$\langle\sigma_\delta\rangle$	%	1.0	0.3
ε_N	μm	1.0	0.2

The scaling of the emittance growth generated by a misaligned quadrupole can be approximated by

$$\left(\frac{\Delta\varepsilon}{\varepsilon_0}\right)_{\eta} \sim \frac{\sigma_\delta^2}{\varepsilon_N}, \tag{4}$$

where σ_δ is the rms relative energy spread in the quadrupole. Applying the relative changes of Table 5 to the scaling in Eq. (4) indicates that this emittance growth in linac-2 is reduced by a factor of 0.45 at 0.1 nC. Quadrupole alignment tolerances are then effectively looser at low-charge. Other linac sections have similarly looser tolerances.

Transverse Wakefields

A misaligned RF structure will generate a transverse kick which varies along the bunch and can also dilute the emittance. The effect is dependent on the total bunch charge and is reduced for shorter bunch lengths. The relevant low-charge parameter changes for linac-2 are listed in Table 6.

Table 6. Changes to the relevant wakefield parameters in linac-2.

Ne	nC	1.0	0.1
σ_z	mm	0.29	0.10
ε_N	μm	1.0	0.2

The scaling of the emittance growth generated by the transverse wakefields of an RF structure can be approximated by

$$\left(\frac{\Delta\varepsilon}{\varepsilon_0}\right)_\perp \sim \frac{N^2\sigma_z}{\varepsilon_N}, \qquad (5)$$

where σ_z is the rms bunch length in the structure. Applying the relative changes of Table 6 to the scaling in Eq. (5) indicates that the wakefield emittance growth in linac-2 is just 2% of the high charge case. Transverse wakefields in linac-2 (a major source of emittance growth in reference 1) are therefore effectively eliminated at low charge as a dilution mechanism. This is also true in the other linac sections.

Incoherent Synchrotron Radiation

The incoherent synchrotron radiation (ISR) of the high energy electrons in the BC2 chicanes can also dilute the emittance. The relative emittance dilution increases for a smaller nominal emittance. The relevant low-charge parameter changes for BC2 are listed in Table 4.

The scaling of the emittance growth generated by ISR in a constant length chicane can be approximated by

$$\left(\frac{\Delta\varepsilon}{\varepsilon_0}\right)_{\text{ISR}} \sim E^6\frac{|R_{56}|^{5/2}}{\varepsilon_N}, \qquad (6)$$

where E is the electron energy in the chicane. Applying the relative changes of Table 4 to the scaling in Eq. (6) will indicate a large increase of the ISR generated emittance growth published in reference 1 (*i.e.* $\Delta\varepsilon/\varepsilon_0 \approx 1.4\%$ at $R_{56} \approx 35$ mm and $E = 6$ GeV). The energy of the chicane system has, however, been altered since the publication of reference 1 from 6 GeV to 4.54 GeV. Including this energy scaling in Eq. (6), and also assuming the chicanes of BC2 are unchanged in physical layout with respect to reference 1, gives an ISR relative emittance growth which is nearly unchanged with respect to reference 1 (*i.e.* $\Delta\varepsilon/\varepsilon_0 \approx 1.3\%$ at 0.1 nC and 4.54 GeV).

These effects summarize the most important emittance dilution mechanisms of the accelerator. In all cases the effect is significantly reduced or of a similar and tolerable level as studied in reference 1. For the accelerator, the low-charge option is an attractive one if the injector can produce the electron beam of Eqs. (1) and (2).

Undulator Wakefields

The electron energy spread generated by longitudinal wakefields in the undulator vacuum chamber is dependent on both bunch charge and bunch length. Since the undulator bunch length is unchanged with respect to reference 1 in this study and the temporal bunch distribution is still quite uniform in shape (see Fig. 1), the undulator wakefields will be diminished according to the bunch charge. The approximate, worst-case (*i.e.* most bunch-length-sensitive) scaling[6] of the surface roughness (SR) wakefield energy spread is

$$\left(\frac{\sigma_E}{E_0}\right)_{SR} \sim \frac{N}{\sigma_z^2}\,. \qquad (7)$$

The approximate, scaling of the resistive-wall energy spread is

$$\left(\frac{\sigma_E}{E_0}\right)_{RW} \sim \frac{N}{\sigma_z^{3/2}}\,. \qquad (8)$$

A reduction in charge by a factor of ten, for a constant bunch length, then implies a reduction in the wakefield induced energy spread by a factor of ten. This applies to both the resistive-wall and the surface roughness wakefields. A significantly rougher surface, lower conductivity, or a reduction in the vacuum chamber radius might be tolerated at low charge. Alternatively, it may be possible to consider a further reduction in the final bunch length (*e.g.* $24\,\mu$m $\rightarrow 12\,\mu$m) at 0.1 nC such that the FEL saturation length is reduced. In this case the wakefield-generated energy spread is still reduced with respect to the high-charge case. This may allow some operational compensation of the inevitable uncertainties in undulator fabrication and alignment. In any case, the optional parameters associated with a range of operating points provide a highly desirable flexibility in machine configurations.

4 Diagnostics

The low charge bunch introduces several technical problems associated with the electron beam diagnostics. For example, the existing beam position monitors (BPMs) of the SLAC linac are designed for a much higher bunch charge (1 to 6 nC)[7]. The BPMs presently provide an rms resolution of ~10 μm at 4-5 nC. At the level of 0.1 nC the BPM resolution may suffer significantly (*e.g.* >100 μm) to the point of rendering steering and feedback systems ineffective. Also, the proposed BPMs in the LCLS undulator are expected to have a resolution of ~1 μm/nC[1]. The resolution of 1-2 μm required for beam-based undulator alignment may not be achievable at 0.1 nC. The alignment must, therefore, be done at 1 nC. Furthermore, the wire scanners in the linac, which are critical for emittance measurements and corrections[8], will also suffer a reduced signal strength and must measure a beam profile which is approximately a factor of two smaller given the 0.2-μm transverse emittance. The wire diameters may need to be reduced.

A partial solution is to set up the accelerator and undulator at 1-nC and then reduce the charge. The trajectories must then remain constant which may be difficult to confirm. Although a 20-30 μm resolution is adequate in the linac, some of the BPMs will probably require increased amplification to accommodate steering and trajectory feedback systems that support prolonged low-charge operations.

5 Conclusions

Operating the LCLS at a reduced bunch charge is very appealing in terms of abating most of the phase space dilution mechanisms in both the accelerator and the undulator. The nominal FEL saturation length can be preserved by injecting a much smaller electron beam emittance which is also generally much easier to preserve in the accelerator due to the reduced bunch charge. Electron beam diagnostics in the accelerator and undulator must be able to accommodate stable operations at the low charge. This may require upgrading some existing hardware and new specifications for future diagnostics. The scaling relations of Eqs. (1) and (2) need experimental verification before this mode of operation can be treated as a practical option. A partial move in this low charge direction may still, however, be available as an alternate operating mode.

6 References

[1] *LCLS Design Study Report*, SLAC-R-521, (1998).

[2] C. Pellegrini, X. Ding, J. Rosenzweig, *Output Power Control in an X-Ray FEL*, PAC-99, New York, NY, March 1999.

[3] J.B. Rosenzweig, and E. Colby, Proceedings of the Conference on Advanced Acceleration Concepts, AIP vol. 335, p. 724 (1995).

[4] The shorter rms bunch from the injector (0.72 mm rather than 1 mm) is based on Parmela calculations by A.D. Yeremian of the gun and 150-MeV booster linac with 1 nC in a rectangular temporal distribution on the cathode.

[5] *LiTrack* was written by Karl Bane at SLAC.

[6] For this worst-case, inductive model see, for example: G. Stupakov, et. al., *Effects of Beampipe Roughness on X-Ray FEL Performance*, submitted to Physical Review Special Topics: Accelerators and Beams, March, 1999.

[7] This fact was pointed out by Marc Ross.

[8] Since emittance dilution is less severe at low-charge the linac wire scanners may be less critical in this mode.