SLAC-PUB-14510

Preliminary study on two possible bunch compression schemes at NLCTA

Yipeng Sun*
SLAC, Stanford, CA 94025, USA

In this paper, two possible bunch compression configurations are proposed and evaluated by numerical simulation in the Next Linear Collider Test Accelerator (NLCTA) at SLAC. A bunch compression ratio up to 20 could be achieved under a perfect condition, without consideration for the timing jitter and other error sources.

1. Overview

The NLCTA is a test accelerator built at SLAC, which is approximately 42 meters long and composed of X-band acceleration structures [1]. The main aim of building NLCTA is to develop and demonstrate the X-band rf acceleration technologies for the next generation linear collider, with a relatively high acceleration gradient between 50 MV/m and 100 MV/m.

The current operation configuration of NLCTA features a thermionic-cathode electron gun at its starting point which generates an electron beam with an energy of 5 MeV [1]. This is followed by a roughly 1.5 meter long X-band acceleration structure which boosts the electron beam energy to 60 MeV. Then there is a four-dipole magnetic chicane which is 6 meters long and provides a first order longitudinal dispersion of $R_{56} = -73mm$. Next the electron beam passes by several matching quadrupoles and can be accelerated further to 120 MeV through another one-meter-long X-band acceleration structure. After that, there are three small chicanes downstream, with a total first order longitudinal dispersion of $R_{56} = -10mm$.

A sketch of the main components of NLCTA is shown in Figure 1 below, where the total length of this accelerator is 45 meters.

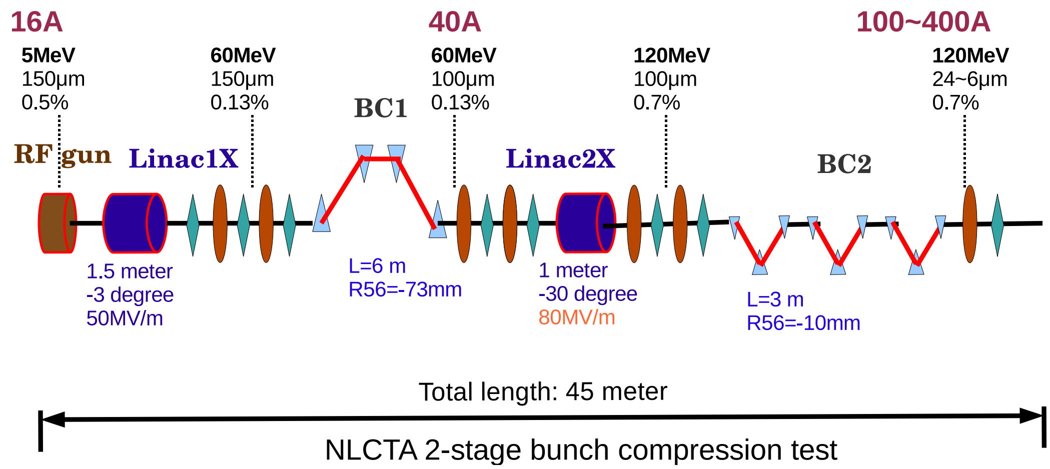

Figure 1: Sketch of the NLCTA accelerator, from the thermal RF gun to the end, with a total length of 45 meters.

*Electronic address: `yisun@slac.stanford.edu`

SLAC National Accelerator Laboratory, Menlo Park, CA 94025

Work supported in part by US Department of Energy contract DE-AC02-76SF00515.

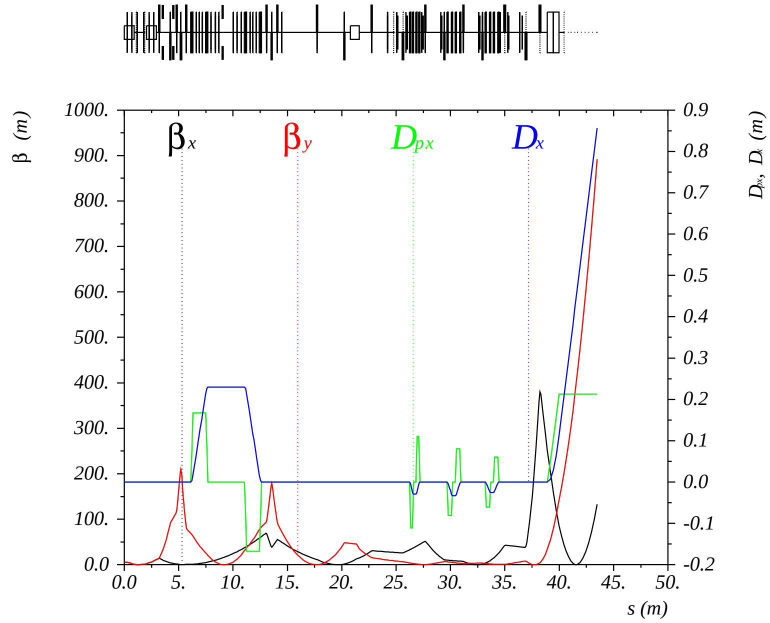

Figure 2: NLCTA optics of the normal operating configuration for ECHO [6].

Free Electron Lasers (FELs), proposed by J. Madey and demonstrated for the first time at Stanford University in 1970s [2] [3], use the lasing of relativistic electron beam traveling through a magnetic undulator, which can reach high power and can be widely tunable in wavelength. Linac based FEL source can provide sufficient brightness, and a short X-ray wavelength down to angstrom scale, which promises in supporting wide range of research experiments. In order to have an electron beam lasing coherently in an undulator, one needs a very bright beam in all three dimensions. In other words, one needs an electron beam with very short bunch length (high intensity), very small transverse emittance and very small energy spread.

Most FELs currently being operated, commissioned, constructed or proposed are based on RF acceleration in a frequency range from L-band (1 GHz) to C-band (6 GHz). As RF frequency goes higher, wake fields effects tend to be much stronger and jitter tolerances are tighter. To demonstrate that X-band acceleration structures can be applied in constructing an FEL, one could perform bunch compression experiments at NLCTA as a first step, and investigate tolerances on timing jitter, misalignments etc.. Another important point is to evaluate the transverse emittance growth in this bunch compression process.

In the following sections, two possible bunch compression schemes are proposed to be tested at NLCTA. Elegant [4] 3-D simulation is performed to evaluate these two schemes, with wake fields, space charge and coherent synchrotron radiation (CSR) effects included. One million macro particles are adopted in the numerical simulations. The simulation starts with an electron beam of 20 pC at a beam energy of 5 MeV. The initial RMS bunch length is taken as 0.5 ps at such a low bunch charge, and the RMS energy spread is 5×10^{-3}. The normalized transverse emittance is 1 mm.mrad.

2. Two stage bunch compression

The first proposed bunch compression scheme is based on two stage bunch compressors, which is a similar configuration as the current running LCLS FEL [5]. No hardware modification is needed and the current operation

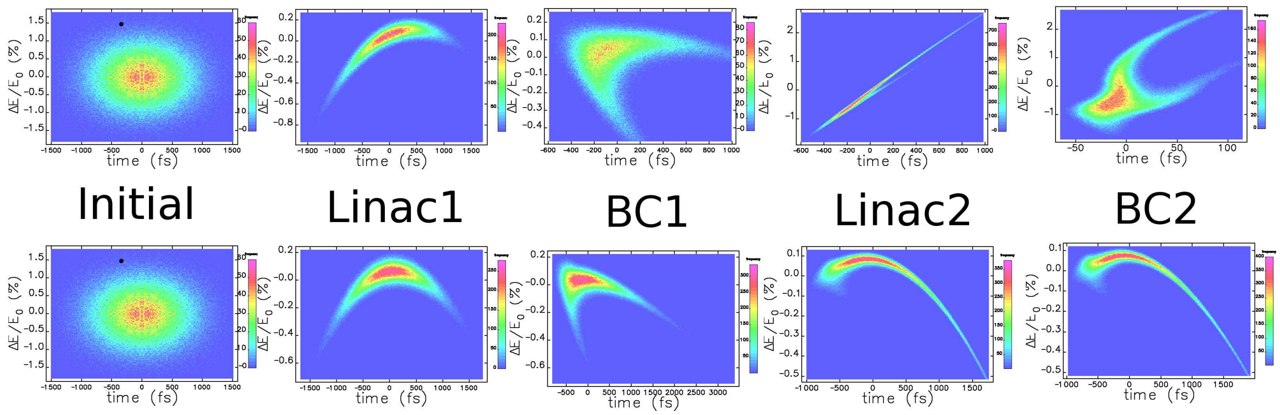

Figure 3: Longitudinal phase space evolution. Observing locations: initial, Linac1 end, bunch compressor one end, Linac2 end, bunch compressor two end (from left to right). Top: two stage bunch compression discussed in this section; bottom: on crest acceleration without compression.

configuration of NLCTA ECHO program is adopted, with its first order optics shown in Figure 2 [6].

In the first linac section, the electron beam energy is boosted from 5 MeV to 60 MeV on an RF phase of -2.5 degree. Then the electron beam passes by the first big chicane where all twelve quadrupoles between the four dipole magnets are turned off. This six-meter-long four dipole chicane provides a first order longitudinal dispersion of $R_{56} = -77mm$. The electron bunch length is compressed by a factor of 2 in this first stage bunch compression.

Next step the electron beam passes by the second linac, where its energy is increased from 60 MeV to 120 MeV, on an RF phase of -35 degrees. This establishes a relatively large energy correlation (chirp). Then the electron bunch passes by three subsequent small chicanes which overall longitudinal dispersion equals $R_{56} = -10mm$. In this second bunch compression stage, the electron bunch length is further compressed by a factor of 10. The final electron bunch length is 26 fs, with a peak current over 0.4 kA. The advantage of doing two (multi) stage bunch compression is discussed in other papers [5] [7] [8] and not repeated here.

The evolution of the longitudinal phase space is shown in Figure 3, for a comparison between two cases. One case is the two stage bunch compression described above, with an overall bunch compression ratio of 20. Another case is to accelerate the electron beam on crest, with no bunch compression applied. For the second case, there is some small deformation on the bunch longitudinal profile (shape) due to cross talk between higher order RF curvature and chicane dispersions.

In Figure 4 the bunch current profile (shape) is compared again between these two cases, with or without bunch compression. One observes that under this two stage bunch compression configuration, a quasi linear bunch compression is achieved and the final bunch distribution is close to a Gaussian distribution. The electron bunch length is compressed by 20 times, from an initial value of 500 fs to a final length of 26 fs.

In the bunch compression process, the transverse emittance of the electron beam is well preserved. CSR and space charge effects are relatively weak at a low beam charge of 20 pC. Also a bunch compression ratio of 2 at lower energy (60 MeV) and a bunch compression ratio of 10 at higher energy (120 MeV) are adopted, to better preserve the electron beam brightness. The final longitudinally sliced normalized transverse emittance, and energy spread is shown in Figure 5.

3. One stage bunch compression with optics linearization

A second possible bunch compression scheme to be tested at NLCTA is based on optics linearization [8]. In this case, the higher order dispersions of the bunch compressor is used to partially cancel the higher order energy correlation (chirp) from RF acceleration, especially for X-band RF system which has a relatively short wavelength.

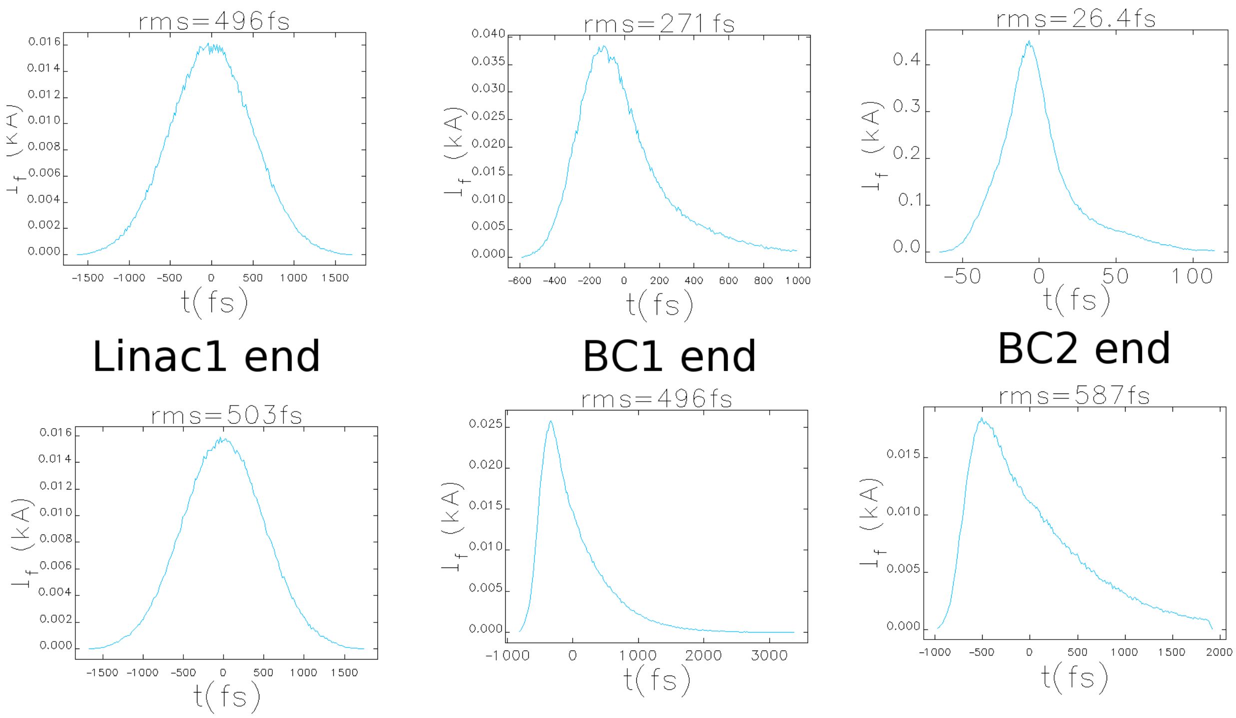

Figure 4: Longitudinal current profile. Observing locations: Linac1 end, bunch compressor one end, bunch compressor two end (from left to right). Top: two stage bunch compression discussed in this section; bottom: on crest acceleration without compression.

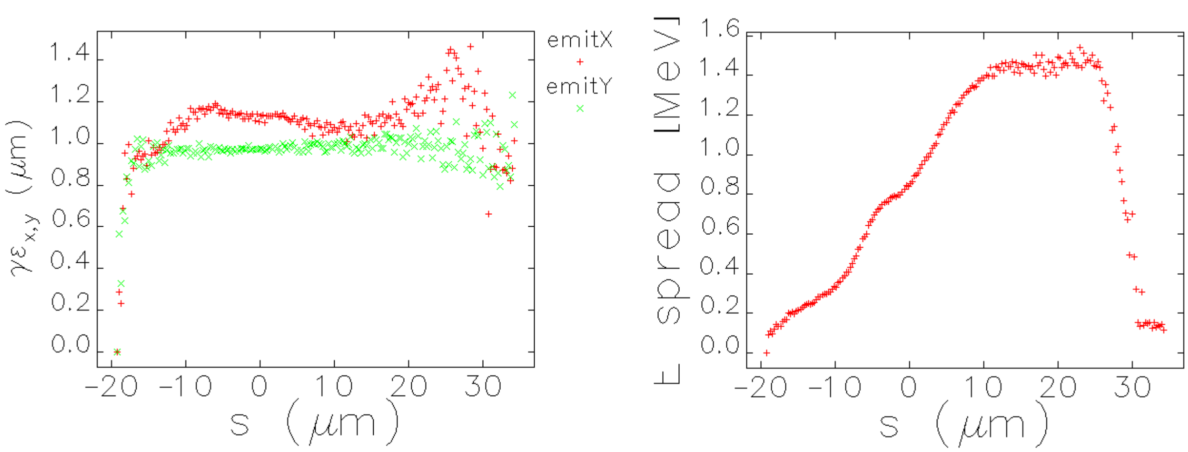

Figure 5: Electron beam sliced properties at the end of NLCTA with two stage bunch compression. Final beam energy is 120 MeV. Left: longitudinally sliced normalized transverse emittance; right: longitudinally sliced energy spread.

Again the details are not discussed here which can be found in the reference listed below [8]. Three sextupole magnets need to be installed in the NLCTA first chicane, in order to achieve the required first order and second order longitudinal dispersions (R_{56} and T_{566}), as well as to close the first order (R_{16} and R_{26}) and second order transverse dispersions (T_{166} and T_{266}).

An example of such an optics solution is shown in Figure 6. In all one needs four dipole magnets, ten quadrupole magnets and three sextupole magnets to form such a bunch compressor. Midplane symmetry is kept which is essential

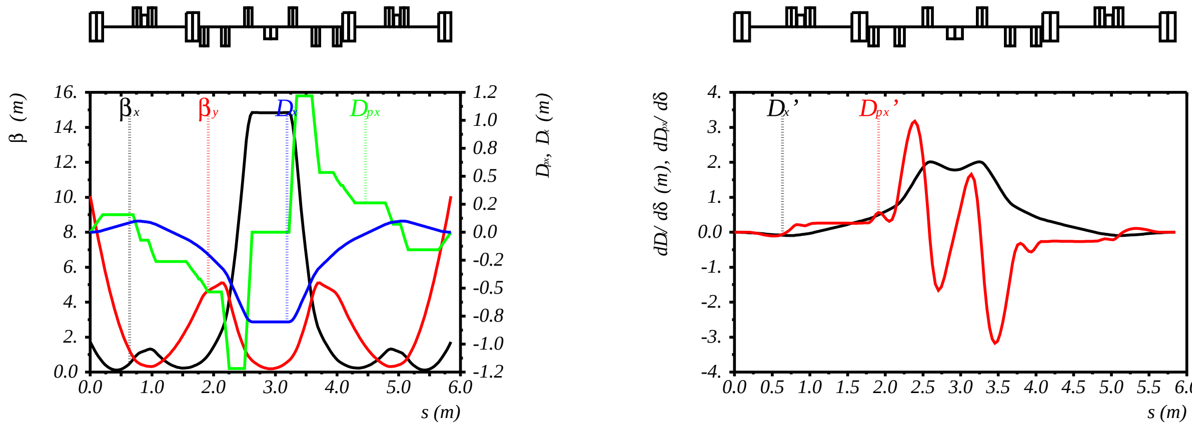

Figure 6: An example optics of a chicane with quadrupole and sextupole magnets. Left: first order optics; right: second order horizontal optics.

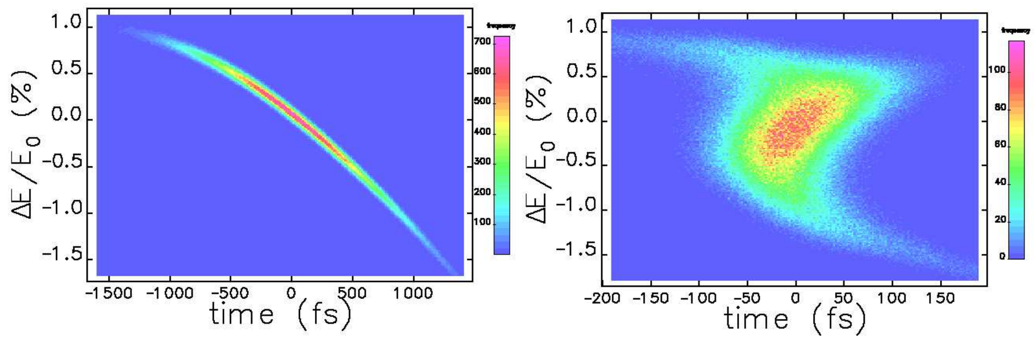

Figure 7: Longitudinal phase space evolution. Left: at linac1 end; right: after bunch compressor with optics linearization.

for cancellations between optics aberrations of quadrupole and sextupole magnets. The total length of this bunch compressor is kept the same as the old chicane which is six meters.

As this bunch compressor has an opposite sign of first order longitudinal dispersion R_{56}, compared with the normal four dipole chicane, the falling slope of the RF wave needs to be adopted. In this configuration, the electron beam is accelerated from 5 MeV to 60 MeV on an RF phase of +8 degrees. It then passes by this bunch compressor and gets compressed in bunch length quasi linearlly with the assistance of the designed dispersions, R_{56} and T_{566}. The longitudinal phase space is shown in Figure 7. Here over compression is adopted, in order to remove the energy correlation (de-chirp) afterwards with longitudinal wake fields. A compression ratio of 10 is achieved here, with a final RMS bunch length of 50 fs.

As discussed above, one important point is to preserve the transverse emittance of the electron beam during the bunch compression process. The final longitudinally sliced normalized transverse emittance, energy spread and final current profile is shown in Figure 8.

X-band RF system is much more sensitive to timing jitter due to its shorter wavelength, than S-band or C-band RF systems. According to LCLS experiences, timing jitter can be controlled within 50 fs [5]. For a two stage bunch compression configuration, one could make use of the longitudinal wake field effects and partially cancel the timing jitter effect [5] [7], which is not applicable for a single stage compression discussed in this section. Final bunch length

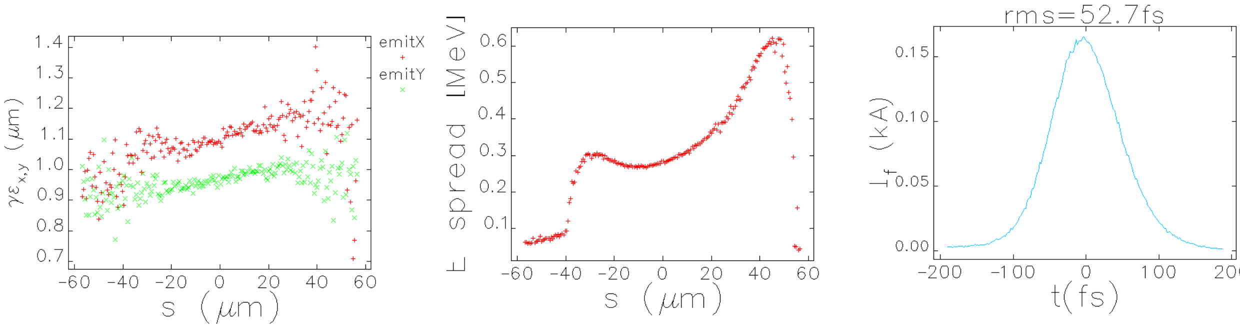

Figure 8: Electron beam sliced properties at the end of bunch compressor with optics linearization. Electron beam energy is 60 MeV. Left: longitudinally sliced normalized transverse emittance; middle: longitudinally sliced energy spread; right: current profile. A compression ratio of 10 is achieved in this single stage.

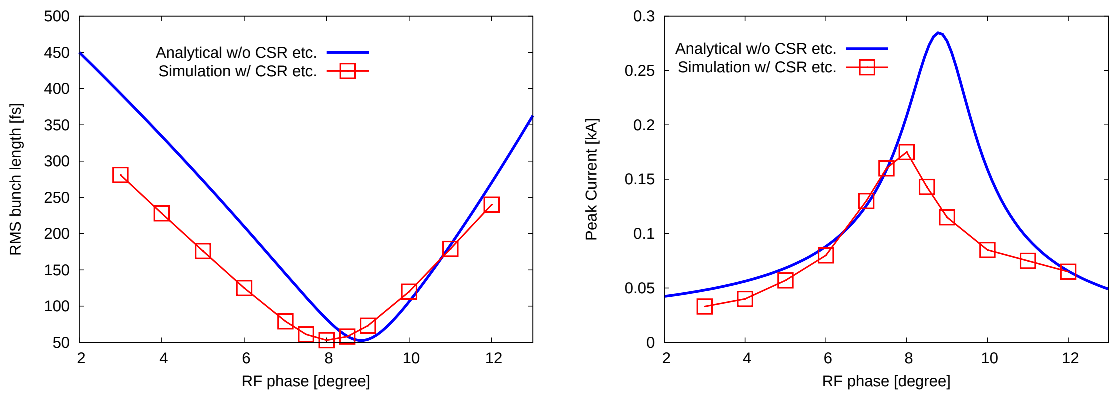

Figure 9: Final bunch length and peak current versus RF phase, in the single stage bunch compression with optics linearization. Left: final bunch length; right: peak current. Differences between analytical results and simulation results are due to CSR and other collective effects.

and peak current is scanned over a range of RF phase, and the simulation results are shown in Figure 9, along with the analytical estimations.

4. Acknowledgement

The authors would like to thank C. Adolphsen, P. Emma, Z. Huang, T. Raubenheimer and J. Wu for helpful discussions.
This work was supported by the DOE under Contract DE-AC02-76SF00515.

References

[1] NLCTA Conceptual Design Report, SLAC-Report-411, 1993.
[2] J. Madey, J. Appl. Phys. **42**, 1906 (1971).
[3] D. A. G. Deacon, L. R. Elias, J. M. J. Madey, G. J. Ramian, H. A. Schwettman, and T. I. Smith, Phys. Rev. Lett. 38, 892 (1977).
[4] M. Borland, “elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation”, Advanced Photon Source LS-287, (September 2000)

[5] Linac Coherent Light Source Conceptual Design Report, SLAC-R-593, SLAC (2002); P. Emma *et al.*, Nature Photonics **4**, 641-647 (2010).
[6] Mark Woodley, private communication, 2010.
[7] Yipeng Sun, SLAC Report No: SLAC-PUB-14445, SLAC-PUB-14367, SLAC-PUB-14445 (2011).
[8] Yipeng Sun, SLAC Report No: SLAC-PUB-14511 (2011).