

# HIGH-BRIGHTNESS SASE STUDIES FOR THE CLARA FEL

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## Abstract

The Compact Linear Accelerator for Research and Applications (CLARA) is a proposed 250 MeV FEL test facility to be constructed at STFC Daresbury Laboratory in the UK [1]. This paper presents study of a scheme for the temporal and spectral stabilisation of the SASE output. A feasibility study for the operation of the FEL in a novel High-Brightness SASE mode is presented. Electron beam delays are introduced between undulator sections to disrupt the localised collective FEL process, increase the radiation coherence length and reduce the rms bandwidth. This may extend the range of electron bunch lengths appropriate for the generation of temporally coherent single spike SASE FEL pulses.

## INTRODUCTION

In the process of Self-Amplified Spontaneous Emission (SASE) a relativistic electron bunch passes through an undulator field and a collective instability in the coupled electron/radiation system amplifies the initial incoherent spontaneous emission produced by the electron bunch. As the electron bunch progresses down the undulator it slips back with respect to the radiation by one resonant wavelength  $\lambda_r$  per undulator period  $\lambda_w$ . Over one gain length the slippage is one cooperation length  $l_c = \lambda_r/4\pi\rho$  where  $\rho$  is the usual FEL parameter [2]. The cooperation length is thus a scale length for the localised collective process and parameterises the development of temporal coherence. Autonomous regions of the system develop independently from the local noise and at saturation the pulse comprises a series of radiation spikes which are uncorrelated in phase and separated by  $\Delta s \lesssim 2\pi l_c$  [3].

The addition of a series of unequal electron bunch delays between undulator modules increases the slippage rate and removes the dependence of  $\Delta s$  on  $l_c$  so that the SASE spike spacing can be increased giving a corresponding narrowing of radiation bandwidth and increase in coherence length  $l_{coh}$ . The delays must be unequal to prevent the build-up of sideband frequencies which increase the bandwidth and modulate the pulse temporal profile. This scheme, which is an extension of earlier studies [4], is known as High-Brightness SASE (HB-SASE) [5] and shares the concept of enhancing the slippage to improve the radiation temporal coherence with other proposals [6-7]. The concept of improved temporal coherence through slippage enhancement has also been demonstrated in proof-of-principle experiments over a limited parameter range [8-9].

In this paper the HB-SASE scheme is applied to the CLARA VUV FEL to assess its feasibility using two different sequences of electron beam delays: a series of random delays centred about a mean and a series of delays based on a prime number sequence. It is expected that the number sequence will be more effective because

it will eliminate any accidental correlations between sideband frequencies found when using random delays.

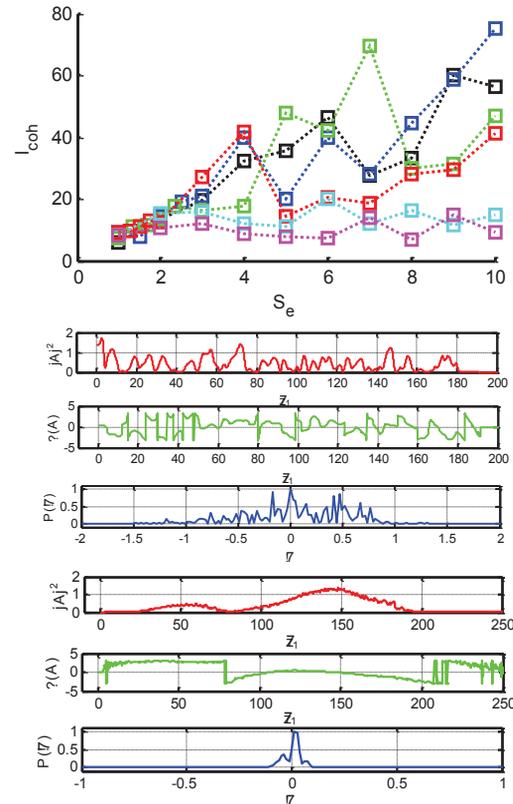


Figure 1 Top: Long pulse simulations - an increase in  $l_{coh}$  is observed for  $l_w \lesssim 2.0$ , (1.73 m). Output measured at saturation. Figure 1 Middle and Bottom: scaled power profile, radiation phase and frequency spectrum for  $S_e = 1.0$  and  $S_e = 10.0$ .

## SIMULATION SETUP AND NOTATION

The CLARA FEL radiator section consists of seven 1.5 m long undulator modules with 1.1 m intra-module gaps for quadrupole, diagnostic section, vacuum components and electron beam delay/phase shifter. The notation adopted is that the delays increase the electron path length by  $\delta$  so that the total slippage per module (undulator and chicane) is  $s = l + \delta$ , with  $l = N_w \lambda_r$  the natural slippage from the undulator of  $N_w$  periods. The parameter  $S_e = (l + \delta)/l$ , with  $\delta$  the mean applied delay, is therefore the slippage enhancement factor so that for normal SASE (no applied delays)  $S_e = 1$ .

A modified version of the 1D code FELO [10] that solves the universally scaled FEL equations was used to model the system. In this scaling distance along the undulator axis is scaled by the 1D gain length, so that undulator length  $l_w = N_w \lambda_w / l_g$ , and coordinate within the reference frame of the propagating electron bunch is scaled by the cooperation length so that  $l_e = L_b / l_c$ . Gaps

between undulators are not simulated and the delay  $\delta$  is applied before each undulator as a forward shift of the radiation field relative to the electron bunch.

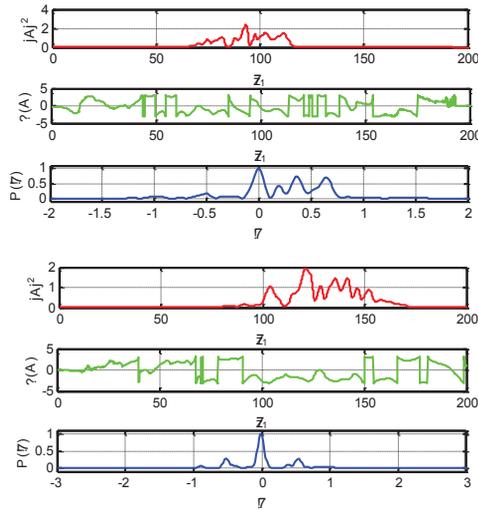


Figure 2: CLARA parameters: scaled power profile, radiation phase and frequency spectrum for (top)  $S_e = 1.0$  (bottom)  $S_e = 7.0$ .

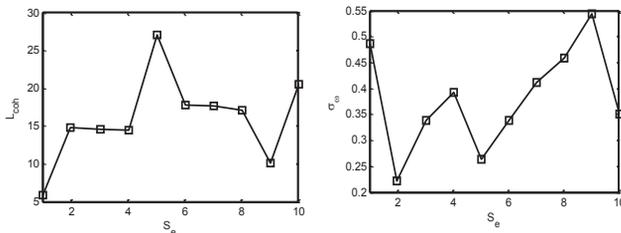


Figure 3:  $l_{coh}$  and  $\sigma_\omega$  for the total range of random delays simulated.

## RANDOM DELAYS

### Long Electron Bunches

As a first study a long electron bunch was used, with  $l_e = 250$ . Simulations were performed for  $l_w = 0.5 - 4.0$  (equivalent to  $L_w = 0.43 - 3.47\text{m}$ ) scanning  $S_e$  from 1 to 10. These long bunches provide statistical weight to the results although they do not represent real CLARA bunches. Figure 1 (top) shows that the increase in  $l_{coh}$  with  $S_e$  is greater for shorter undulator lengths. A factor of 6 increase is seen for  $l_w = 0.5$ , with a transition to no increase for the longest  $l_w$ . Figure 1 (middle) and (bottom) show the significant narrowing of bandwidth, corresponding smoothing of the power profile and stabilising of radiation phase over the pulse for  $l_w = 0.5$ , for  $S_e = 1$  and  $S_e = 10$ . Shorter undulator sections, and hence more frequent delays, are seen to be more effective at disrupting the conventional SASE interaction. The improvement in temporal coherence provided by HB-

SASE is greatest when  $l_w \lesssim l_g$  and  $\delta \lesssim l_c$ . Nevertheless, some increase in  $l_{coh}$  is observed for  $l_w \lesssim 2.0$ .

### CLARA Parameters

For CLARA nominal parameters (RMS bunch length 250 fs, bunch charge 250 pC and  $\rho = 0.003$ ,) the scaled undulator length is  $l_w = 2.19$ , therefore the criteria  $l_w \lesssim l_g$  is not satisfied and the undulator length is in the transition region between coherence enhancement and no coherence enhancement (see Fig. 1 (top)). It is therefore expected that the coherence length enhancement provided by HB-SASE will be small. In the following sections we investigate this further.

Figure 2 shows a comparison between  $S_e = 1$  (no delay) and  $S_e = 7$  (again using random delays). A factor 2 increase in  $l_{coh}$  from 7.15 to 16.33 is observed. However there is no clear trend for the bandwidth  $\sigma_\omega$ , as seen in Fig. 3, and it remains around the initial value of 0.47. This is due to the 2 distinct sideband modes that can be seen in Fig. 2 (bottom). Such sidebands are visible in most spectra and are observed in the mode-coupled FEL scheme [11] which uses constant delays. For the CLARA FEL saturation is reached in only seven undulators so any sideband modes which are common between delays are significant and also not necessarily removed by randomised delays. This is not such a problem for shorter undulators because more delays are applied before saturation. To remove the sideband modes in a controlled way a series of delays based on a prime number sequence may be used [4].

## PRIME NUMBER DELAYS

The delay sequence  $\delta_n = (P_n l_w / 2)(\delta_s - l_w)$  was applied, where  $P$  is the prime number sequence and  $\delta_s$  is a scaling factor. The idea is that the sequence of total delays  $s_n = l_w + \delta_n$  form a prime number sequence so that no common supported sideband frequencies exist over all delays.  $P_1 = 17$  was chosen so that the appropriate total delay could be applied while  $\delta_n > 0$  for all delays. The scale factor was applied to match the total delay up to saturation to that applied previously using random delays. This was to enable comparison between the two schemes. Figure 4 (top) shows the spectra from four independent SASE ( $S_e = 1$ ) simulations, each starting with a different shot noise seed, while Fig. 4 (bottom) shows four independent HB-SASE simulations with  $S_e = 6$ . Figure 5 shows the variation of coherence length and bandwidth as a function of  $S_e$ . It is seen that the maximum coherence length and minimum bandwidth do not correspond to the same slippage enhancement, and the  $S_e = 6$  case shown in Fig. 4 (bottom) is a compromise working point. At this point  $l_{coh} = 25$  and  $\sigma_\omega = 0.23$  so both have improved by a factor of approximately four compared to SASE.

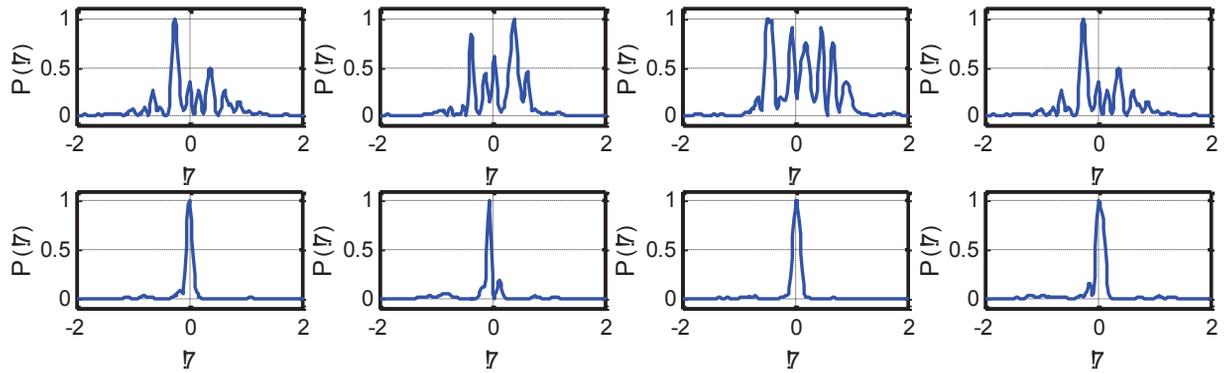


Figure 4: Spectra from 4 independent SASE simulations with (top)  $S_e = 1.0$  and (bottom)  $S_e = 6.0$ .

The HB-SASE spectra are centred about the resonant frequency with sidebands greatly reduced compared with the results using random delays. Comparison of Fig. 3 and Fig. 5 also shows that the use of prime number sequence delays gives a smoother improvement in performance as the total delay is gradually increased, compared to using random delays.

The mean SASE spike spacing for  $S_e = 1$  is  $18\mu\text{m}$ , agreeing with the theoretical  $\Delta s \lesssim 2\pi l_c = 16\mu\text{m}$ . For  $S_e = 7$  the spike spacing  $\Delta s = 42\mu\text{m}$ . The increase is therefore significant but less than the slippage enhancement factor.

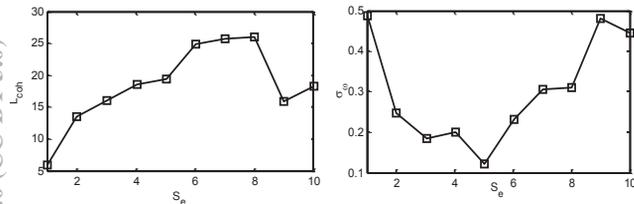


Figure 5:  $l_{coh}$  and  $\sigma_\omega$  for the total range of prime delays simulated.

## CONCLUSION

Using 1D simulations it has been shown that the use of random electron delays between undulators in a High-Brightness SASE scheme provides a clear improvement in temporal coherence for short undulator sections, but as these sections are increased to the length to be used in CLARA the enhancement is lost. This problem is resolved by the use of a sequence of delays based on a prime number sequence. This gives a more controlled elimination of the sideband modes which otherwise increase the bandwidth. This is particularly important for the CLARA FEL which uses relatively long undulator modules and hence has fewer delays. Application of the scheme to the CLARA FEL standard lattice may give at least a factor of four improvement in longitudinal coherence. This may allow fully temporally coherence output from electron bunches which would otherwise be

too long to generate single-spike SASE output. Further studies to improve the efficacy of HB-SASE, such as inserting extra delays within undulators are being carried out, as well as with Genesis 1.3 simulations to include effects in 3D.

## REFERENCES

- [1] J. A. Clarke et al, The Conceptual Design of CLARA, a Novel FEL Test Facility for Ultrashort Pulse Generation, these proceedings.
- [2] R. Bonifacio, C. Pellegrini and L. Narducci, Opt. Commun. 50 (1984) 373.
- [3] R. Bonifacio, L. De Salvo, P. Pierini, N. Piovela and C. Pellegrini, Phys. Rev. Lett. 73 (1), 70 (1994).
- [4] N. R. Thompson, D. J. Dunning and B. W. J. McNeil, Proc. of IPAC'10, Kyoto, Japan, TUPE050, p. 2257.
- [5] B. W. J. McNeil, N. R. Thompson and D. J. Dunning Phys. Rev. Lett. 110, 134802 (2013).
- [6] J. Wu, A. Marinelli and C. Pellegrini, Generation of Longitudinally Coherent Ultra High Power X-Ray FEL Pulses by Phase and Amplitude Mixing, Proc. of FEL 2012, also SLAC-PUB-15348, 2012.
- [7] D. Xiang, Y. Ding, Z. Huang, and H. Deng, Phys. Rev. ST Accel. Beams 16, 010703 (2013).
- [8] J. Wu and C. Pellegrini, Private Communication
- [9] T. Raubenheimer, Proc. of HBEB 2013, <http://pbpl.physics.ucla.edu/HBEB2013/Talks/TorRaubenheimerHBEB13.pdf>
- [10] B.W.J. McNeil, G.R.M. Robb, D. Dunning and N.R. Thompson, Proc. of FEL 2006, Berlin, Germany, MOPPH011 (2006).
- [11] N.R. Thompson and B.W.J. McNeil, Phys. Rev. Lett. 100, 203901 (2008).