BEAM QUALITY AND TRANSPORT STABILITY SIMULATIONS IN ECHO ENABLED HARMONIC GENERATION

J. Henderson, B.W.J. McNeil, SUPA, University of Strathclyde, Glasgow, UK
D.J. Dunning, ASTeC, STFC Daresbury Laboratory & Cockcroft Institute, UK

Abstract

The method of Echo Enabled Harmonic Generation (EEHG) [1, 2] is a possible method of achieving coherent short wavelengths in an FEL amplifier. In this paper the effects of noise variations and some of the important parameters affecting the stability of the final harmonic bunching of the electron beam are investigated numerically.

INTRODUCTION

The so-called echo effect has been studied for many years in phenomena such the photon echo [3], spin echoes [4], and the echo effect in circular accelerators [5]. The EEHG scheme for improving temporal coherence in FELs was recently proposed in [1] and developed in [2]. The EEHG scheme allows high harmonics of a seed laser to be generated with high frequency up-conversion efficiency. The scheme consists of two modules of an undulator and dispersive section, both of which energy modulate and then disperse the beam. The effect of this is to give the beam a complicated phase space structure containing high harmonic components. The notation set out in [1, 2] gives the energy modulation parameters as $A_1 = \Delta E_1/\sigma_E$ and $A_2 = \Delta E_2/\sigma_E$, where σ_E is the rms energy spread of the beam and ΔE_1 and ΔE_2 are the values of energy modulation imparted on the beam in the first and second undulators respectively. The dispersive parameters in the first and second dispersive sections are $B_1 = R_{56}^{(1)} k_1 \sigma_E / E_0$ and $B_2 = R_{56}^{(2)} k_2 \sigma_E / E_0$ respectively, with R_{56} the standard of dispersion term.

PARAMETER ANALYSIS

The four main parameters of EEHG scheme are the two energy modulation parameters A_1, A_2 and the dispersive parameters B_1 and B_2. These parameters have varying degrees of control over the bunching factor. A study of the bunching factor with respect to these parameters was reported in [6]. This paper takes that approach one step further through analysing the bunching factor stability with respect to two simultaneously varying parameters. The bunching factor was calculated at the centre of the beam using $b = \left| N^{-1} \sum \exp(-iazk_1) \right|$ where $a = 24$ (the harmonic factor).

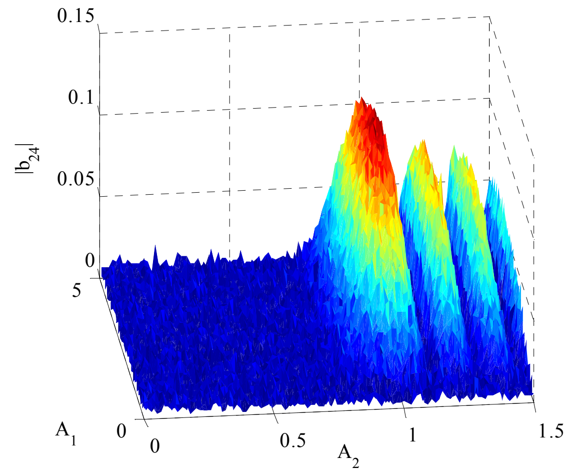

Figure 1: The bunching factor as a function of the two energy modulation parameters A_1 and A_2.

Figure 1 shows the dependence of the bunching factor on the energy modulation parameters A_1 and A_2. The bunching factor shows remarkable stability in relation to the first energy modulation parameter A_1. Moderate adjustment to the second energy modulation parameter A_2 can result in the bunching factor being significantly reduced. Figure 1 shows three distinct peaks in bunching parameter with variation of A_2; the first peak occurs at $A_2 = 1$ and the second peak at $A_2 = 1.2$. Between the peaks the bunching is significantly reduced. The stability of the EEHG scheme to variation in the first modulation section is considered in Fig. 2.

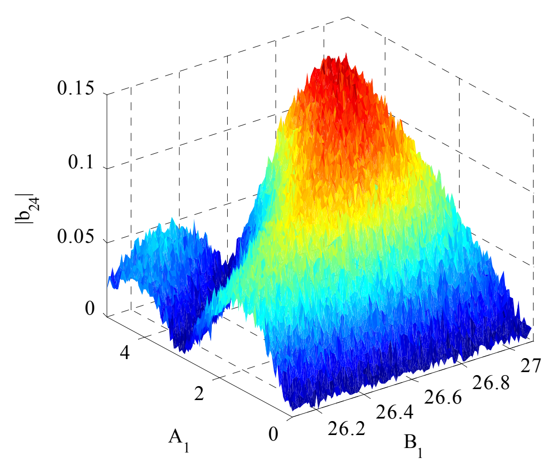

Figure 2: The bunching factor as a function of the first energy modulation parameter A_1 and the first dispersive parameter B_1.

The bunching factor at the 24th harmonic is very stable with variation in the parameters A_1 and B_1 of the first EEHG section. The bunching factor is also relatively insensitive to variation of the parameters A_1 and B_2 (as shown in Fig. 3), the first undulator parameter and second dispersive parameter. In the cases of Fig. 2 and 3, a change in one parameter could be compensated through a change in the other. The bunching factor as a function of A_2 and B_2 is shown in Fig. 4, and as a function of A_2 and B_1 in Fig. 5. In both cases there are three distinct peaks, potentially allowing a choice of bunching factor maximum to be selected. In Fig. 6 the bunching factor is not aligned with either axis, implying that a change in parameter B_2 can be compensated for by adjusting parameter B_1.

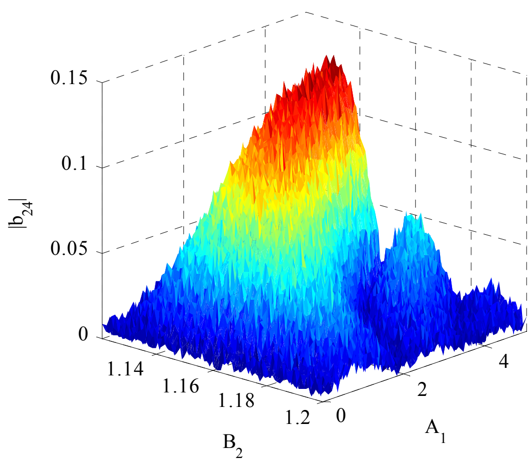

Figure 3: The bunching factor as a function of the first energy modulation parameter A_1 and the second dispersive parameter B_2.

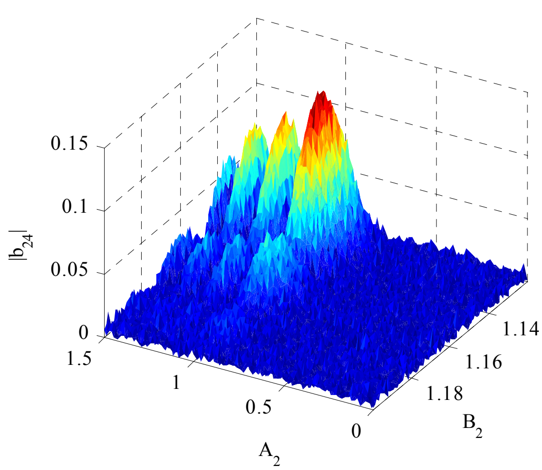

Figure 4: The bunching factor a function of the second energy modulation parameter A_2 and the second dispersive parameter B_2.

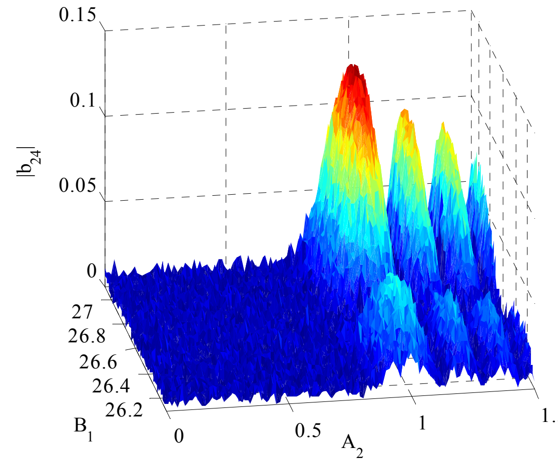

Figure 5: The bunching factor as a function of the second energy modulation parameter A_2 and the first dispersive parameter B_1.

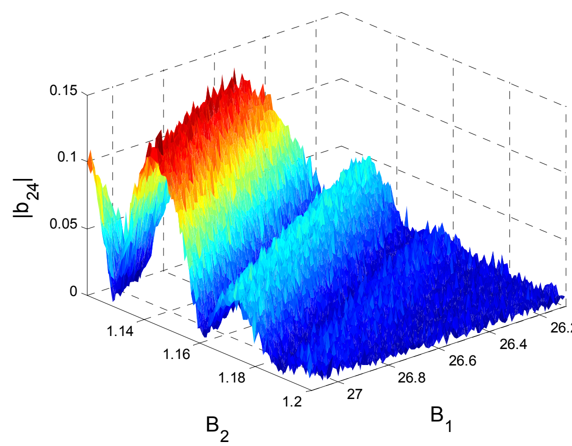

Figure 6: The bunching factor as a function of the first dispersive parameter B_1 and the second dispersive parameter B_2.

EEHG NUMERICAL MODELLING

EEHG simulations were carried out using a 1D code written in MATLAB. These simulations are based on the notation set out in [1, 2]. A dimensionless energy deviation variable is defined as $p = (E\text{-}E_0)/\sigma_E$. The beam goes through four manipulations. Firstly the beam is given an energy modulation in the first undulator which modifies the energy coordinates as $p' = p + A_1 \sin(k_1 z)$. The first dispersive section modifies the longitudinal coordinates as $z' = z + pB_1/k_1$. These two steps are repeated in the second EEHG section but the values of A_2 and B_2 are generally significantly lower. This is to prevent the delicate microstructure of the beam generated in the first EEHG section from being washed out. The following parameters were used in the parameter analysis simulations: the energy modulation parameters were $A_1 = 5$, $A_2 = 1$ and the dispersive parameters

$B_1 = 27.01$, $B_2 = 1.14$. The beam parameters were $E_0 = 1.2$ GeV (average beam energy), rms energy spread of $\sigma_E = 150$ keV and bunch length of 12 µm. The two seed lasers were chosen to have the same wavelength of 240 nm. These parameters generate bunching at the 24th harmonic (10 nm) of the initial seed laser, with a bunching factor of $b_{24} = 0.1249$. The phase space plot of beam at the exit of the last undulator (Fig. 7) reveals the beam's delicate microstructure which contains the higher harmonic components.

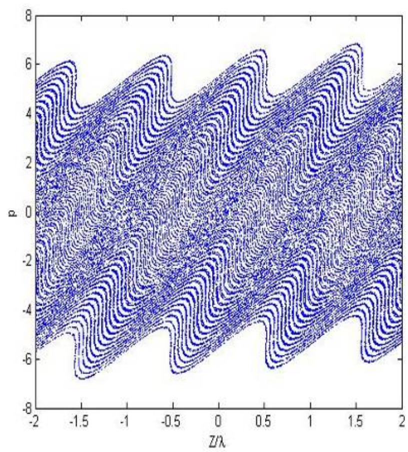

Figure 7: The second undulator and dispersive section generates a large density modulation at the harmonic in the beam's longitudinal plane.

The bunching factor for the 24th harmonic of a 240 nm seed laser (10 nm output) is $b_{24} = 0.1249$. The electron bunch is now sent to a radiator tuned to the resonant wavelength of 10 nm.

Non-Linear Energy Chirp

The effects of a linear energy chirp have been previously analysed in [6]. Here the effects of a non-linear chirp are analysed. To do this, a crude approximation to an electron beam distribution generated from start-to-end simulations of the UK New Light Source [7] was constructed and used in simulations.

The non-linear energy chirp (shown in Fig. 8) has the following approximate parameters: $E_0 = 2.206$ GeV and $\sigma_E = 150$ keV. The energy chirped bunch was sent through an EEHG simulation with the following parameters, $A_1 = 3$, $A_2 = 1$, $B_1 = -26.83$ and $B_2 = -1.14$. This gives a low bunching factor of 0.0090, as might reasonably be expected.

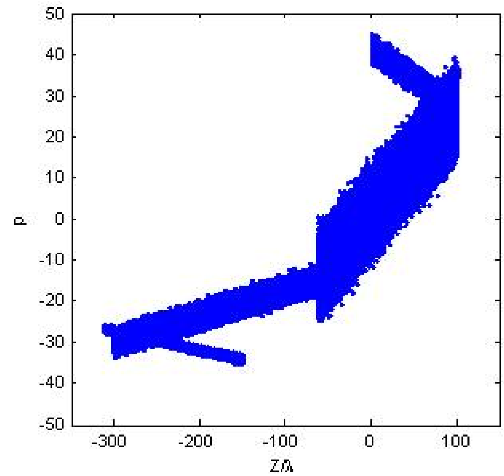

Figure 8: Approximation of a realistic electron beam distribution with non-linear energy chirp, based on [7].

In [6] it was shown that effects of a linear energy chirp can be compensated for by adjusting parameter B_2. This same technique can be applied to a non-linear energy chirp. The bunching factor is increased to 0.07 (as shown in Fig. 9) when parameter B_2 is adjusted ($B_2 = -1.118$). When dispersive parameters B_1 and B_2 are set to 26.83 and 1.14 respectively, the bunching factor value is initially 0.05 and can be increased to 0.07 upon adjusting parameter B_2. Interestingly, the bunching factor variation with B_2 (Fig. 10) for the case when positive parameters are chosen is significantly different for the case when negative parameters are used (Fig. 9). This is due to the slope of the energy chirp (Fig. 8); when the parameters are negative the chirp causes bunch compression giving narrow peaks. However when the parameters are positive the chirp causes bunch expansion giving much wider peaks.

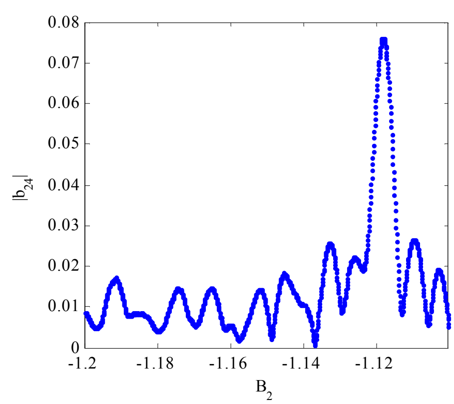

Figure 9: Bunching degradation due to an initial energy chirp can be compensated for by adjusting parameter B_2 (from -1.14 to -1.118).

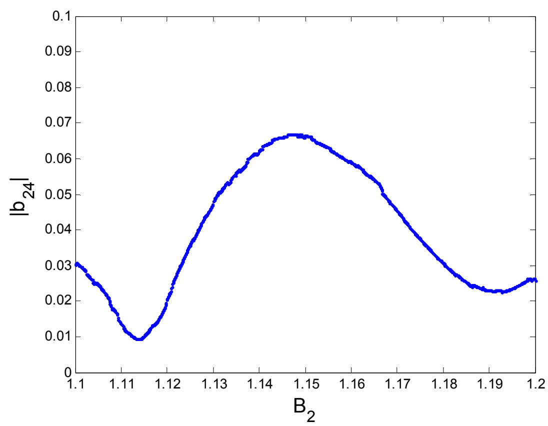

Figure 10: Bunching factor variation with B_2 for the case of positive dispersive parameters, B_1 and B_2.

CONCLUSIONS

The EEHG scheme was modelled and electron bunch phase space evolution through the system was shown. Non-ideal effects were considered and a technique for overcoming energy chirps was demonstrated. Stability analysis was carried out for the energy modulation and dispersive parameters of the two modulator sections through simultaneously varying these parameters in pairs. This analysis revealed ways in which parameter variation can be compensated and also the potential to loosen the constraints on parameter selection. This type of analysis will be crucial when designing and fine tuning an EEHG FEL.

REFERENCES

[1] G. Stupakov, Phys. Rev. Lett. 102, 074801 (2009).

[2] G. Stupakov, D. Xiang, Phys. Rev. ST Accel. Beams 12, 030702 (2009).

[3] N.A. Kurnit, I.D. Abella and S.R. Hartmann, Phys. Rev. Lett. 13, 567 (1964).

[4] E. L. Hahn, Phys. Rev. 80,580 (1950).

[5] G. Stupakov, SSC Laboratory Report No. SSCL-579, 1992; G. Stupakov and S. Kauffmann, SSC Laboratory, Report No. SSCL-587, (1992).

[6] Z. Huang, et al., Effects of energy chirp on echo-enabled harmonic generation free- electron lasers, Preprint SLAC-PUB-13547, SLAC (2009).

[7] Proc. 31st International Free Electron Laser Conference (FEL 09), Liverpool, UK, 23-28 Aug 2009, CI Preprints, Cockcroft-09-25 (2009).