INDUCING STRONG DENSITY MODULATION WITH SMALL ENERGY DISPERSION IN PARTICLE BEAMS AND THE HARMONIC AMPLIFIER FREE ELECTRON LASER

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Abstract

We present a possible method of inducing a periodic density modulation in a particle beam with little increase in the energy dispersion of the particles. The flow of particles in phase space does not obey Liouville's Theorem. The method relies upon the Kuramoto-like model of collective synchronism found in free electron generators of radiation, such as Cyclotron Resonance Masers and the Free Electron Laser. For the case of an FEL interaction, electrons initially begin to bunch and emit radiation energy with a correlated energy dispersion which is periodic with the FEL ponderomotive potential. The relative phase between potential and particles is then changed by approximately 180 degrees. The particles continue to bunch, however, there is now a correlated re-absorption of energy from the field. We show that, by repeating this relative phase change many times, a significant density modulation of the particles may be achieved with only relatively small energy dispersion. A similar method of repeated relative electron/radiation phase changes is used to demonstrate supression of the fundamental growth in a high gain FEL so that the FEL lases at the harmonic only.

INTRODUCTION

Many electron beam generators of radiation rely upon a Kuramoto-like collective synchronism [1] that bunches the electrons with respect to the radiation phase resulting in coherent emission. The bunching process occurs due to a correlated energy dispersion in the electrons induced by the radiation field. This mechanism is readily understood from the electron flow in phase space as shown schematically in Fig. 1. Here ϑ is a generic electron phase parameter and p is the corresponding energy. If the relative electron/radiation phase were to be switched by $\Delta\vartheta = \pi$ rad then it can be seen from Fig. 2 that the hyperbolic and elliptic points of the instantaneous separatrix are transposed. (By "instantaneous separatrix" we mean the sepratrix that would govern electron flow in phase space if the radiation field was not allowed to evolve thereafter in the interaction.) It can be seen that although the electrons will continue to bunch, the electron energy dispersion will be partially reversed. By successive repetition of the relative $\Delta\vartheta = \pi$ rad phase switching it may be possible to bunch the electrons in phase space without a correspondingly large increase in the energy spread of the beam. In this way the local, or 'slice', longitudinal emittance of the beam would be reduced.

A novel method that may allow lasing of a high gain FEL

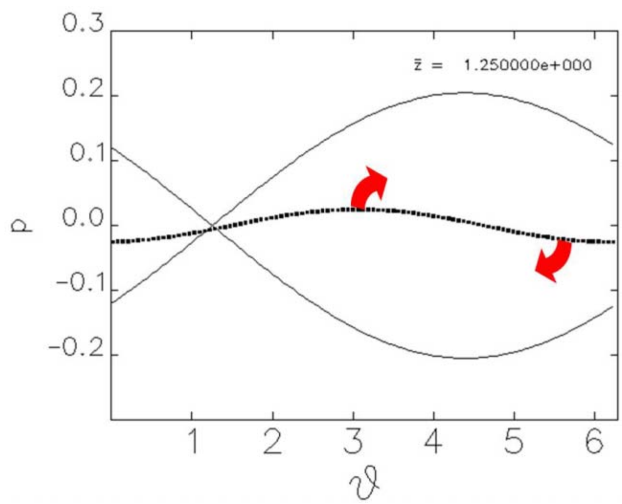

Figure 1: Electron trajectories in phase-space (ϑ, p) at beginning of FEL-type interaction. The solid line is the instantaneous separatrix and the red arrows indicate the direction of electron phase flow.

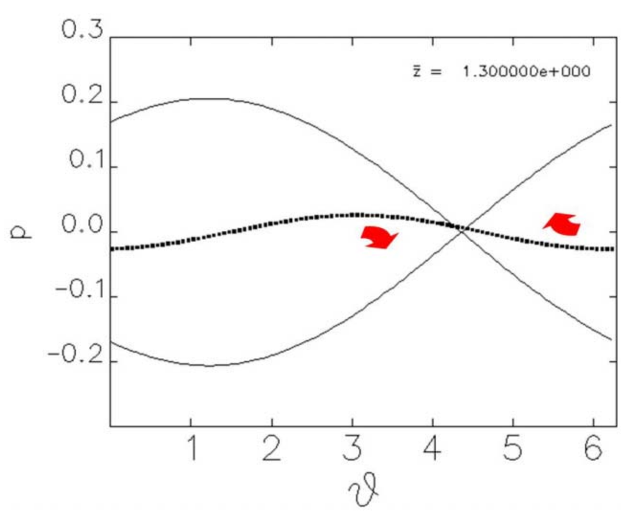

Figure 2: Electron trajectories in phase-space at beginning of FEL-type interaction as Fig. 1 but immediately following a relative $\Delta\vartheta = \pi$ phase change between electrons and radiation.

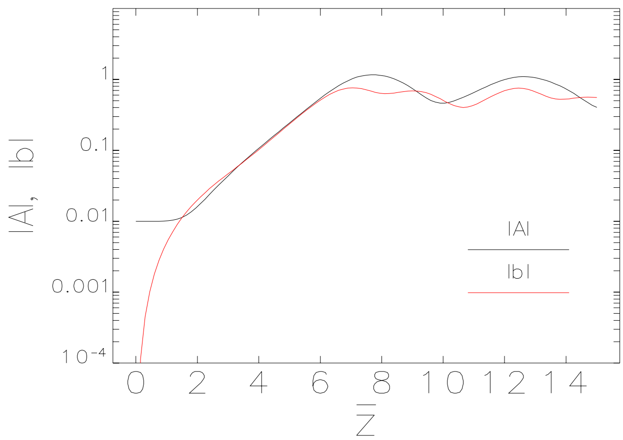

Figure 3: FEL type evolution of the scaled field modulus $|A|$ and electron bunching parameter $|b|$ as a function of scaled distance, $\bar{z}$, through the interaction region.

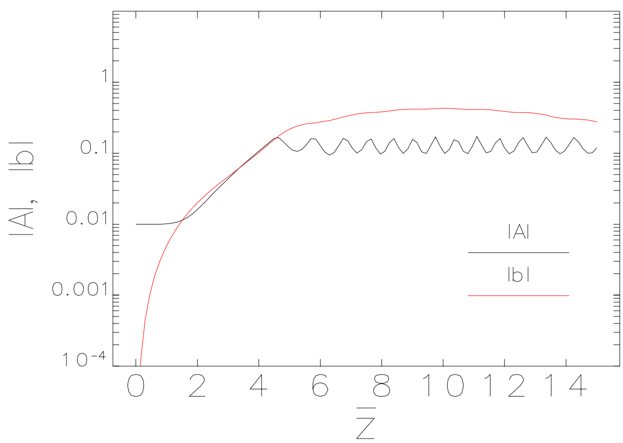

Figure 4: FEL type evolution of the scaled field modulus $|A|$ and electron bunching parameter $|b|$ as a function of scaled distance, $\bar{z}$, through the interaction region including the effects of a series of relative electron/radiation phase changes.

at a harmonic of the fundamental is also presented.

BUNCHING WITH SMALL ENERGY DISPERSION

In order to demonstrate the principle, the universally scaled equations describing an FEL amplifier interaction in the Compton limit [2] were solved for an electron beam with a scaled Gaussian energy spread of $\sigma_p = 0.1$ and an initial scaled seed field modulus of $|A| = 10^{-2}$. Fig. 3 shows the usual exponential instability through to saturation and beyond. Fig. 4 shows the result of a series of $\Delta\vartheta = \pi$ rad phase changes applied when $|A| \gtrsim 0.17$. Although the exponential evolution is seen to cease, the electron bunching continues to grow. This growth is not at the expense of a significant increase in the energy spread of the beam, however, as can be seen from Fig. 5 which plots as

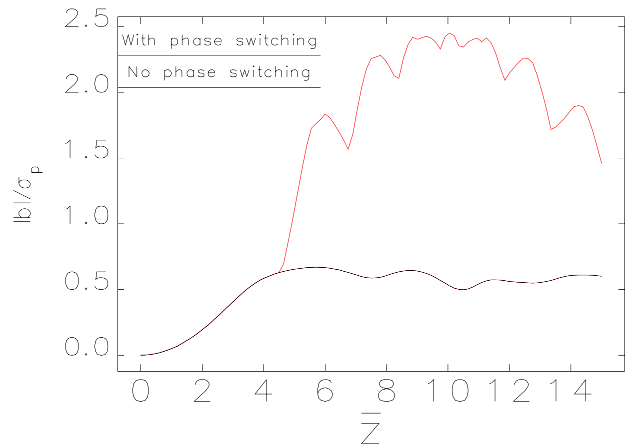

Figure 5: FEL type evolution of the quantity $|b|/\sigma_p$ as a function of scaled distance, $\bar{z}$, through the interaction region.

a 'figure of merit' the quantity $|b|/\sigma_p$ for the same simulation as shown in Fig. 4. This quantity can be considered a measure of how densely the electrons are distributed within phase space, with larger values corresponding to a smaller longitudinal slice emittance. It can be seen that the method of $\Delta\vartheta = \pi$ phase switching increases this quantity by a factor ≈ 4 above that obtained from the usual FEL-type interaction. Note that no attempt has been made here to optimise this process and improved values for $|b|/\sigma_p$ may be obtainable by changing the values of $\bar{z}$ at which the phase switches are made and possibly by varying the value of the phase switch $\Delta\vartheta$.

The authors have recently become aware of similar analysis and modelling to the above for a SASE FEL system [3]. The primary objective of Tanaka and Kitamura was to investigate the effects of longitudinal and transverse alignment errors between sections of a multi-sectional undulator lattice on the performance of an FEL operating in the SASE mode, i.e. there is no initial seed field and the FEL amplifier starts from noise. They found that when a series of phase switches $\Delta\vartheta = \pi$ was made between undulator sections then the FEL amplified two sidebands either side of the resonance with reduced energy amplification. We have carried out similar preliminary numerical modelling of a FEL SASE pulse interaction using the model of [4] and have observed a similar behaviour in the steady-state region of a 'top-hat' shaped current pulse evolution. Operation in SASE appears to destroy the electron bunching with reduced energy dispersion effects described by the steady-state model above. When a radiation seed field is introduced with intensity significantly above the SASE noise level, the bunching with low energy dispersion appears more robust and similar improvements to the value of $|b|/\sigma_p$ as shown in Fig. 5 may be attained.

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HARMONIC AMPLIFIER FEL

The ability to vary the relative electron/radiation phase between FEL undulator sections also presents other possibilities, particularly in planar undulators where odd harmonics of the fundamental resonant frequency are also resonant. For a relative phase change of $\Delta\vartheta$ at the fundamental, the relative phase change for the nth odd harmonic field will be $n\Delta\vartheta$. Therefore, for $\Delta\vartheta = 2k\pi/n$ ($k = 1, 2, 3, \ldots ; k \neq n$) the relative electron/radiation phase change for the fundamental will not be an integer multiple of 2π and would be expected to disrupt its exponential gain. For the nth harmonic, however, the relative electron/radiation phase change will be $2k\pi$ and no disruption to the exponential harmonic gain would be expected. It should therefore be possible to disrupt the gain of the fundamental sufficiently to allow the exponential harmonic interaction to dominate.

A numerical simulation demonstrating this effect is shown in Fig. 6 using an electron beam with a scaled Gaussian energy spread of $\sigma_p = 0.1$. The steady-state equations describing harmonic FEL interaction [5] for the fundamental, 3rd and 5th harmonics were solved with $\Delta\vartheta = 4\pi/3$ applied at values of $\bar{z} = 4, 5, 6, \ldots$. In this way, the sequence of relative electron/radiation phase changes for the fundamental and 5th harmonics are non-integer multiples of 2π, whereas for the 3rd harmonic the relative phase changes are 4π. It can be seen that the fundamental and 5th harmonic gain processes are disrupted while the 3rd harmonic growth is exponential to saturation. Note that the scaled fundamental intensity at the beginning of the interaction is two orders of magnitude greater than the harmonics', simulating an input seed field. It could be expected that the coherence properties of this seed may be transferred to the harmonic interaction thereby improving its temporal coherence properties over that obtained from a SASE interaction. Again no attempt has been made here to optimise this process.

Preliminary simulations have also been carried out for a 1D SASE FEL pulse interaction and similar lasing at the 3rd harmonic has been observed.

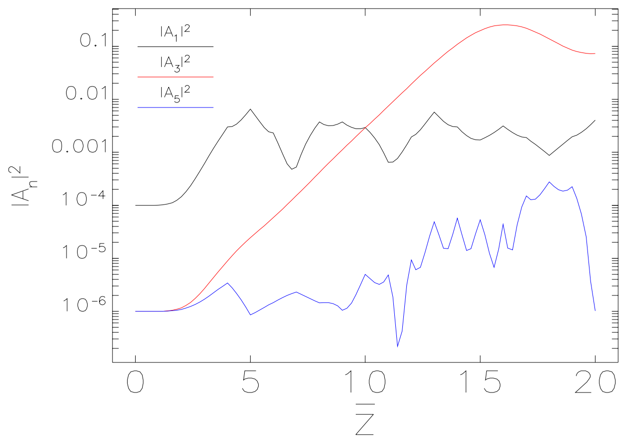

Figure 6: Harmonic Amplifier FEL simulation of the scaled radiation intensities of the the fundamental (black), 3rd (red) and 5th (blue) harmonics. Both fundamental and 5th harmonic evolution is supressed by a series of relative electron/radiation phase changes $\Delta\vartheta = 4\pi/3$.

CONCLUSIONS

It has been shown that the introduction of a series of relative phase changes between particles and radiation interacting in an FEL-type of collective interaction can produce interesting and potentially useful effects. Two distinct processes have been presented in the context of an FEL interaction, although we stress that these interactions could also be more generally realisable in other Kuramoto-like collective synchronism systems and where relative particle/radiation phase changes can be made.

The first interaction demonstrated in proof-of-principle simulations the possibility of bunching electrons at radiation wavelength scales with an energy spread that is significantly smaller than that induced by the FEL interaction alone. This reduces the slice longitudinal emittance and could conceivably be used in combination with other proposals that may transfer a beam's longitudinal and transverse emittance [6], to reduce the emittance of a beam. A further potential application is in the pre-bunching of a beam for use in multi-wiggler harmonic FELs.

The second interaction has the potential to extend to shorter wavelengths the range of operation of a high gain FEL by allowing the interaction at an harmonic to dominate that at the fundamental. This method is particularly suited to FELs constructed from multi-sectional undulators such as that of LCLS in the USA and XFEL in Europe. As these designs already incorporate phase-shifters between undulator sections it may be that the existing designs are already able to explore the possibility of operating in a harmonic lasing mode without any modification.

ACKNOWLEGMENTS

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