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PLASMA ACCELERATOR DRIVEN COHERENT SPONTANEOUS EMISSION

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Abstract

Plasma accelerators [1] are a potentially important source of high energy, low emittance electron beams with high peak currents and generated within a relatively short distance. While novel plasma photocathodes [2] may offer improvement to the normalised emittance and brightness of electron beams compared to Radio Frequency-driven accelerators, a challenge is the energy spread and chirp of the beams, which can make FEL operation impossible. In this paper it is shown that such an energy-chirped beam, with a dynamically evolving current profile due to ballistic bunching, can generate significant coherent radiation output via the process of Coherent Spontaneous Emission (CSE) [3]. While this CSE is seen to cause some FEL-induced electron bunching at the radiation wavelength, the dynamic evolution of the energy chirped pulse dampens out any high-gain FEL interaction.

INTRODUCTION

Significant effort have been dedicated to demonstrating a plasma-based accelerator driven FEL [4–6]. However, next to stability challenges, the inherent by-product of plasma-based accelerators is a relatively large slice energy spread ($\sigma_\gamma/\gamma > \rho$) and a correlated energy spread ('chirp') when compared with RF linacs. In this paper, the dynamics of the electron bunch from a plasma photocathode [2], which can have an inherent negative energy chirp, is explored. One effect, which to the authors knowledge has not been modelled before with such a PWFA plasma photocathode-generated energy chirped beam, is to induce the generation of Coherent Spontaneous Emission (CSE) [3, 7]. CSE arises when the electron pulse has significant *current* gradients over a resonant radiation wavelength. It is shown that for the electron beam parameters used here, such current gradients can be realised when the energy chirped beam undergoes spatial dispersive compression in its propagation direction due to the correlated energy spread [3, 7]. By dominating any normal spontaneous emission, it has been shown in 1D simulations that CSE can also self-seed the FEL interaction in a process called Self Amplified Coherent Spontaneous Emission (SACSE) [8]. The CSE was also shown in 1D to help mitigate the effects of a homogeneous electron energy spread in beams without an energy chirp, significantly reducing the start-up time and enhancing the generation of high intensity, short, superradiant radiation pulses from a poor-quality electron pulse [9].

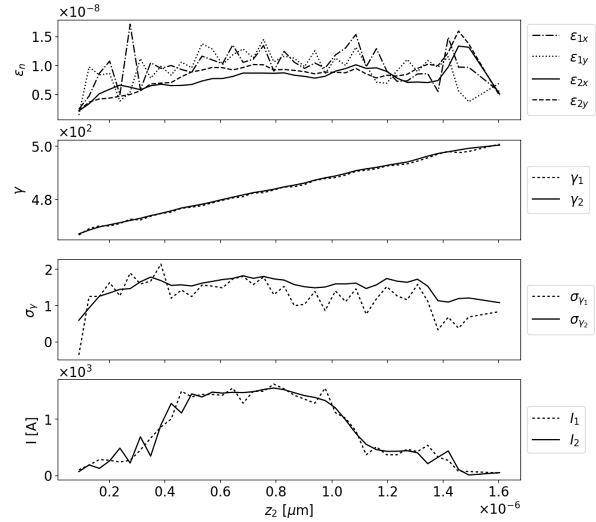

Figure 1: From top, the electron beam normalised emittance ϵ_n, localised Lorentz factor γ, RMS energy spread σ_γ and current I, as a function of window position $z_2 = (ct - z)$ of the beam. In this window, travelling at speed c along the z-axis of the undulator, the head of the electron bunch is on the left, the tail on the right, and the beam will propagate to larger values of z_2 as the beam propagates through the undulator. The dashed plots (index 1) show the original macroparticle beam from the VSim simulation and the solid plots (index 2) show the beam following smoothing and up-sampling to a greater number of microparticles with the correct shot-noise statistics.

ELECTRON BUNCH SIMULATION

A macroparticle distribution is taken from a VSim simulation of a PWFA. These macroparticles have too sparse a phase-space distribution for an accurate FEL simulation as there are too few macroparticles per resonant wavelength and they have unrealistic shot-noise statistics. These macroparticles are converted into a suitable distribution of *microparticles* using the scripts [10] and [11]. The relevant bunch parameters of a microparticle beam are compared to the original beam of macroparticles in Fig. 1. The microparticle distribution has had the correct shot-noise statistics applied as described in [12]. It is seen that the electron beam has a negative longitudinal energy chirp, which is the result of the beam acceleration in the electric field of the nonlinear plasma wave.

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UNAVERAGED FEL SIMULATION

The unaveraged 3D FEL simulation code Puffin was used [13,14] as it is able to model both macroscopic electron beam changes due to the electron beam energy chirp and any CSE and SACSE that may arise. The Ming Xie formalism of [15, 16] was used to chose the planar undulator period λ_u and undulator parameter a_u. The estimated beam parameters of the unchirped beam of Fig. 1 are: $I_{pk} = 1500$ A, $\epsilon_{xy} = 0.01$ mm mrad, $\gamma = 486$, $\sigma_\gamma = 0.3$ %, $Q = 3.6$ pC.

The undulator parameters selected for simulations were $\lambda_u = 0.015$ m and $a_u = 1.0$. The resulting radiation wavelength is $\lambda_r \approx 67$ nm and the FEL parameter at peak current is $\rho = 0.021$. Given that the average slice energy spread is $\sigma_\gamma/\gamma \approx 3 \times 10^{-3}$ the energy spread condition for FEL lasing of $\sigma_\gamma/\gamma \lesssim \rho$ is well satisfied in the absence of an energy chirp. The steady state, Self Amplified Spontaneous Emission (SASE) saturation length is then approximated as $L_{sat} \approx 1.4$ m and saturation power $P_{sat} \approx 2.2$ GW. The electron bunch does not, however, conform to the steady-state approximation as it is only ~ 6 cooperation lengths long, where the cooperation length $l_c = \lambda_r/4\pi\rho$ [17]. This relatively short electron pulse length will result in the output of short, single pulses, at saturation. This type of short pulse operation is in the weak superradiant regime of FEL operation [17] and also results in reduced saturation powers from that of the steady-state, Ming Xie approximation above. The Puffin simulation uses the energy chirped electron bunch distribution output from the PWFA as shown in Fig. 1. The beam of microparticles was matched to the natural focusing channel of the undulator lattice chosen for the simulation as above using the method of [18]. It is seen from the parameters of the chirped pulse, plotted in Fig. 1, that the electron pulse generated by the PWFA has a length of $l_e \approx 24\lambda_r \approx 6l_c$ and has a negative energy chirp in z (positive energy chirp in z_2). During propagation through the undulator, dispersion will cause this short, energy chirped electron bunch to self-compress longitudinally due to rotation in longitudinal phase space, which is significant at these relatively low energies, and it may even 'flip over' in longitudinal phase space [3]. During this process, the electron bunch length may approach that of the resonant wavelength ($l_e \sim \lambda_r$) and consequently would be expected to radiate significant CSE. In what follows the CSE generation due to energy chirped bunch shortening and any FEL processes were modelled self-consistently. The FEL interaction may also amplify CSE in addition to the spontaneous emission due to electron beam shot-noise in the SACSE [8]. As with SASE, given the large energy chirp here, any SACSE process would be expected to be significantly affected. The electron bunch length is plotted as a function of position through the undulator in Fig. 2, and is seen to shorten and flip over before lengthening again.

The energy of the radiation pulse as a function of distance through the undulator emitted by the chirped bunch is shown in Fig. 3 both with and without the FEL interaction included in the simulation. The FEL interaction is 'switched off' in the

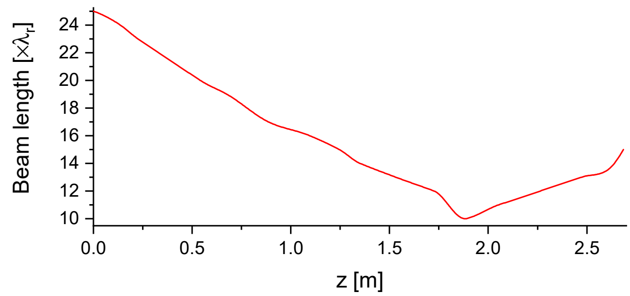

Figure 2: The full electron bunch length in units of resonant wavelentgh. The initial energy chirp at $z = 0$ m is seen to cause the electron pulse to compress and then will decompress longitudinally.

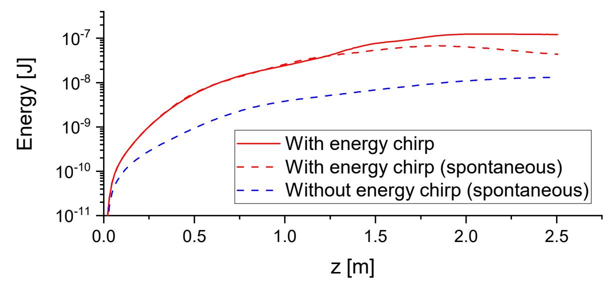

Figure 3: Radiation energy as a function of distance z through the undulator. Two of the plots (red) are for the chirped pulse including (solid) the FEL interaction and (dashed) without the FEL interaction. The case without energy chirp or FEL interaction (blue dashed) gives an energy growth with a quasi-linear dependence with z, corresponding to shot-noise spontaneous emission without significant CSE contribution.

Puffin simulation by artificially de-coupling the electrons from the radiation field. Also shown is the sponteneous emission with the energy chirp artificially removed from the electron bunch. The corresponding average bunching parameters $|\bar{b}|$, for both the chirped and un-chirped electron pulses are shown in Fig. 4.

The radiation pulse 'instantaneous' power (i.e. unaveraged over a radiation wavelength [13]) and electron bunching parameter $|b|$ at saturation, is shown in Fig. 5 as a function of local position z_2. It is seen from the Fig. 2 that the elec-

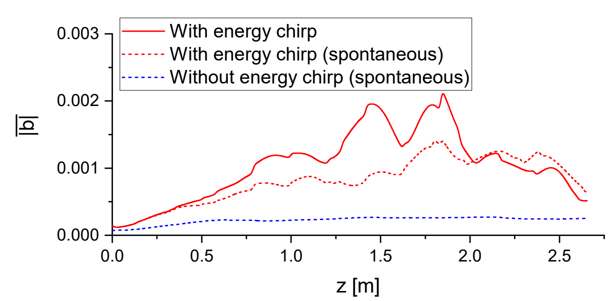

Figure 4: Average bunching parameter evolution for the electron pulse as a function of distance through the undulator both with (solid red) and without (dashed red) the FEL interaction. Also shown is the average bunching for the case of no energy chirp (dashed blue).

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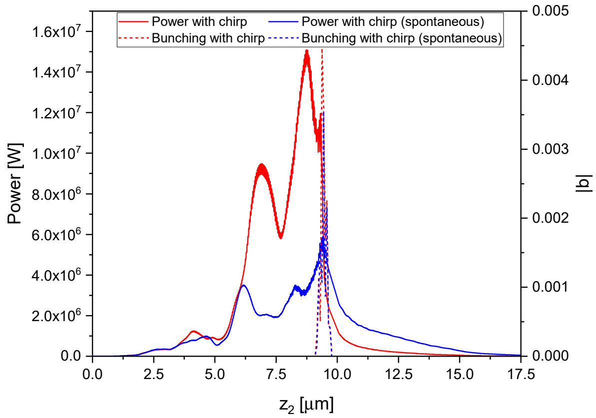

Figure 5: The radiation power profile (solid red) and the electron bunching parameter (dashed red) as a function of $z_2 = (ct - z)$ at $z = z_{sat} = 1.95$ m through the undulator for the energy chirped case and corresponding case for the FEL interaction 'switched off' (solid blue and dashed blue).

tron energy chirp causes the electron bunch to longitudinally compress in phase space and shorten as it propagates through the undulator. At saturation, $z = 1.95$ m, the electron bunch is only ~ 10 resonant radiation wavelengths long. When the FEL interaction is switched off, the electrons then only emit spontaneous emission due to both shot-noise and CSE. Figure 3 shows that the energy growth is not exponential but is proportional to $\sim z^2$, more consistent with CSE [3]. That the radiation energy emitted in the absence of the FEL interaction is similar to that with the FEL interaction, confirms that the emission in both cases arise mainly from CSE. In the absence of any energy chirp or FEL interaction, there is no shortening of the electron pulse and the CSE emission is greatly reduced. The energy growth is then quasi-linear with distance z through the undulator, consistent with incoherent spontaneous emission due to shot-noise only.

The evolution of the mean electron bunching parameter $|\bar{b}|$ of Fig. 4 increases quasi-linearly with distance through the undulator until $z \approx 1.2$ m. This is in broad agreement with the increased bunching due to the dispersive shortening of the electron pulse which causes significant current gradients with respect to the radiation wavelength. It is this type of bunching which drives the Coherent Spontaneous Emission [3] and which may act as a self-generated seed field which can be amplified as SACSE [8, 9]. Also plotted is the electron bunching of the electron pulse in the absence of any energy chirp. As described above, there is no shortening of the electron pulse and the bunching remains approximately constant and at a much smaller value, mainly due to shot-noise, than when the pulse shortens and significant current gradients occur at the radiation wavelength scale. The differences of the radiation emission and electron bunching, between the spontaneous-only case, when the FEL interaction is switched off, and that where the FEL interaction is included in the simulation, can be attributed to a small additional bunching due to SACSE. Some small periodic bunching about the radiation wavelength $\lambda_r \approx 67\,nm$ due to SACSE, can be seen in the evolution of the electron phase-space through the undulator. The lack of any significant FEL gain is consistent with the work of [19] where for negative values of their chirp parameter $\hat{\alpha}$, here $\hat{\alpha} \approx -2$ at $z = 0$ m, FEL power output is greatly reduced from that expected from an un-chirped beam. So while some increased bunching is evident due to the FEL interaction between radiation and electrons, it is not operating in the collective, high-gain mode, significantly reducing the power emitted. Following the minimum of its length, the electron bunch continues to disperse as it propagates through the undulator, flipping over in phase space and indeed re-absorbing some of the emitted radiation and is consistent with that of previous simplified models [3]. Figure 5 (red) plots both the radiation power and electron bunching as a function of local position at saturation. It is seen that the electron pulse bunching, corresponding to the electron pulse at saturation of Fig. 2, is within a small local interval around $z \sim 9.5$ μm. The radiation pulse power for $z_2 < 9.5$ μm has propagated ahead of the electron bunch and is propagating in vacuum.

Figure 5 show results for both simulations with the FEL interaction switched on (red) and off (blue). The radiation is then that due to spontaneous radiation from shot-noise and CSE only. The difference in the power emitted between the two is then due to the FEL interaction as observed from the additional electron bunching of Figs. 4 and 2. The modest increase in output power demonstrates that the FEL is not, however, operating the in the high-gain regime.

CONCLUSION

Using a start-to-end approach, PWFA driven FEL operation was studied numerically using an unaveraged 3D model. The PWFA electron pulse output had a significant quasi-linear energy chirp. This chirp causes the electron pulse to shorten as it propagates through the undulator and emit significant CSE power. This CSE was seen to drive the electrons to give some weak periodic bunching at the resonant radiation wavelength, but not to enter into a collective, high-gain regime where analysis in the steady-state regime (no pulse effects) predicts output powers approximately two orders of magnitude greater. The dynamic shortening of the electron pulse and subsequent emission of CSE as it propagates through the undulator is an effect that is not normally modelled in FEL simulations. Methods to remove the electron beam energy chirp are the subject of on-going research and, if possible, are expected to allow the high gain FEL interaction to develop and output short coherent pulses of high power radiation.

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