Plasma Accelerator Driven Coherent Spontaneous Emission

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- Novel plasma photocathodes [1,2] 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 beams, which can make FEL operation impossible.
- Here, we show that an energy-chirped with 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.

- The initial macroparticle distribution was taken from the VSim PWFA simulation and was converted into suitable format for Puffin[10], for this process the conversion [4] and upsampling [5] scripts were used.
- The relevant parameters of the beam of microparticles are compared to the original beam of macroparticles from the VSim simulation in **Fig.1**. The microparticle distribution has also had the correct shot-noise statistics applied as described in [6].

PARAMETER	VALUE
Peak current	1500 A
Normalised emittance	0.01 mm mrad
Energy (γ)	486
RMS energy spread	0.3 %
Bunch charge	3.6 pC

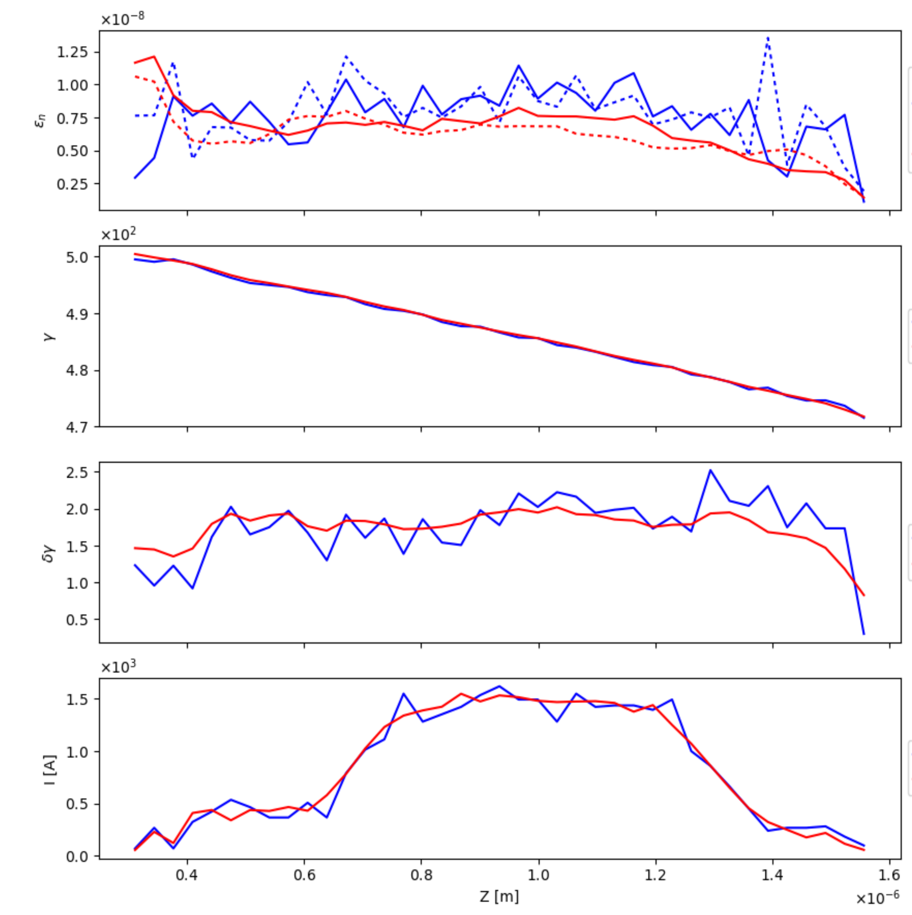

Fig.1 Beam parameters before and after upsampling. The electron pulse generated by the PWFA has a length of l_e~$24\lambda_r$~$6l_c$ and has a negative energy chirp in z (positive energy chirp in z_2).

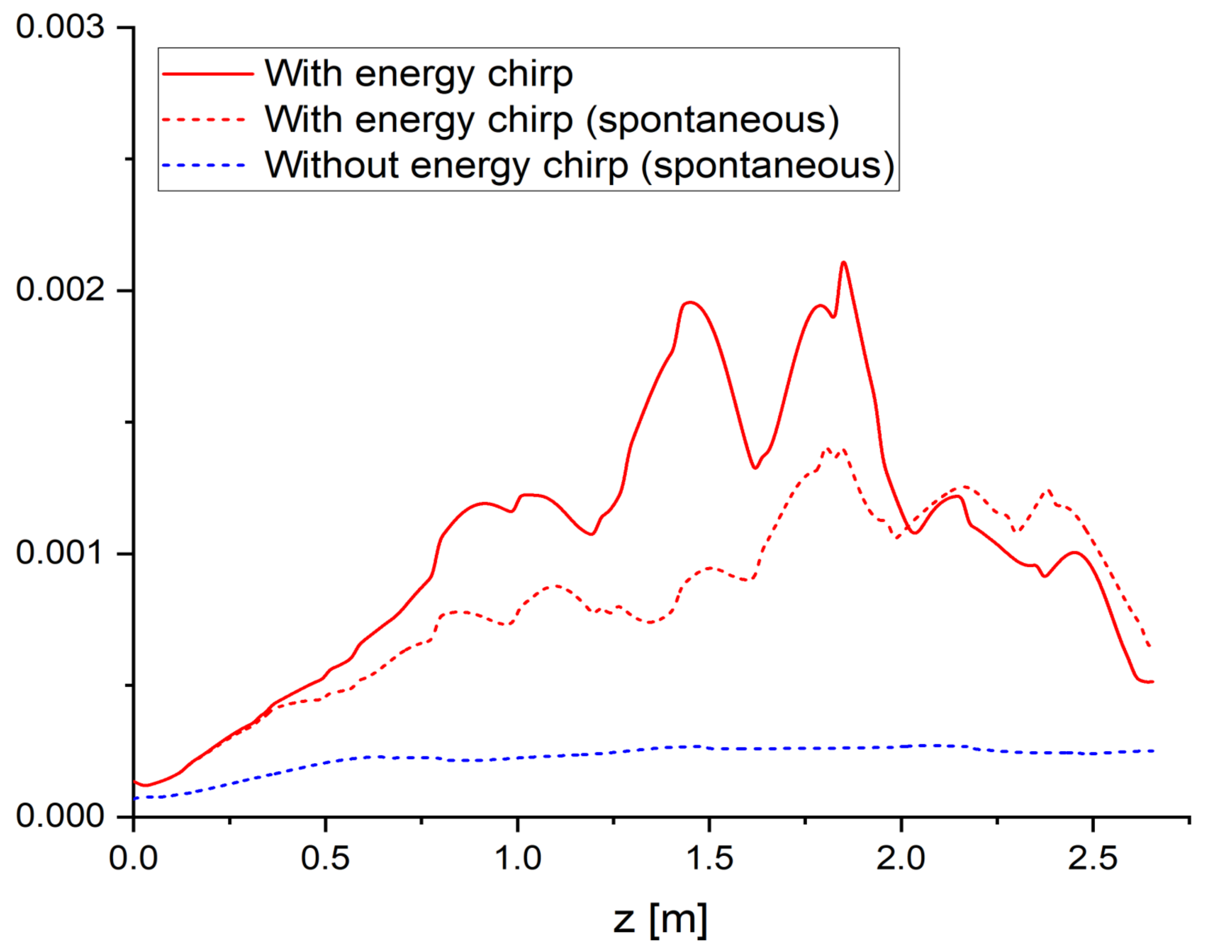

Fig.2 Average bunching parameter evolution for the electron pulse as a function of distance through the undulator.

- The undulator parameters selected for simulations: λ_u= **0.015m, a_u = 1.0**.
- The resulting radiation wavelength is λ_r**~67nm** and the FEL parameter at peak current is **ρ=0.021**.
- Given that the average slice energy spread **σ_γ=0.003** the energy spread condition for FEL lasing of $\sigma_\gamma/\gamma<\rho$ 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}~ 1.4m.** **The electron bunch does not, however, conform to the steady-state approximation as it is only 6 cooperation lengths long.**

- 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] (**Fig.3**). During this process, the electron bunch length may approach that of the resonant wavelength (l_e~λ_r) and consequently **would be expected to radiate significant CSE**.
- It should be noted that the FEL interaction may also amplify CSE in addition to the spontaneous emission due to electron beam shot-noise in a process called **Self Amplified Coherent Spontaneous Emission (SACSE)** [7]. As with SASE, given the large energy chirp here, any **SACSE** process would be expected to be significantly affected.

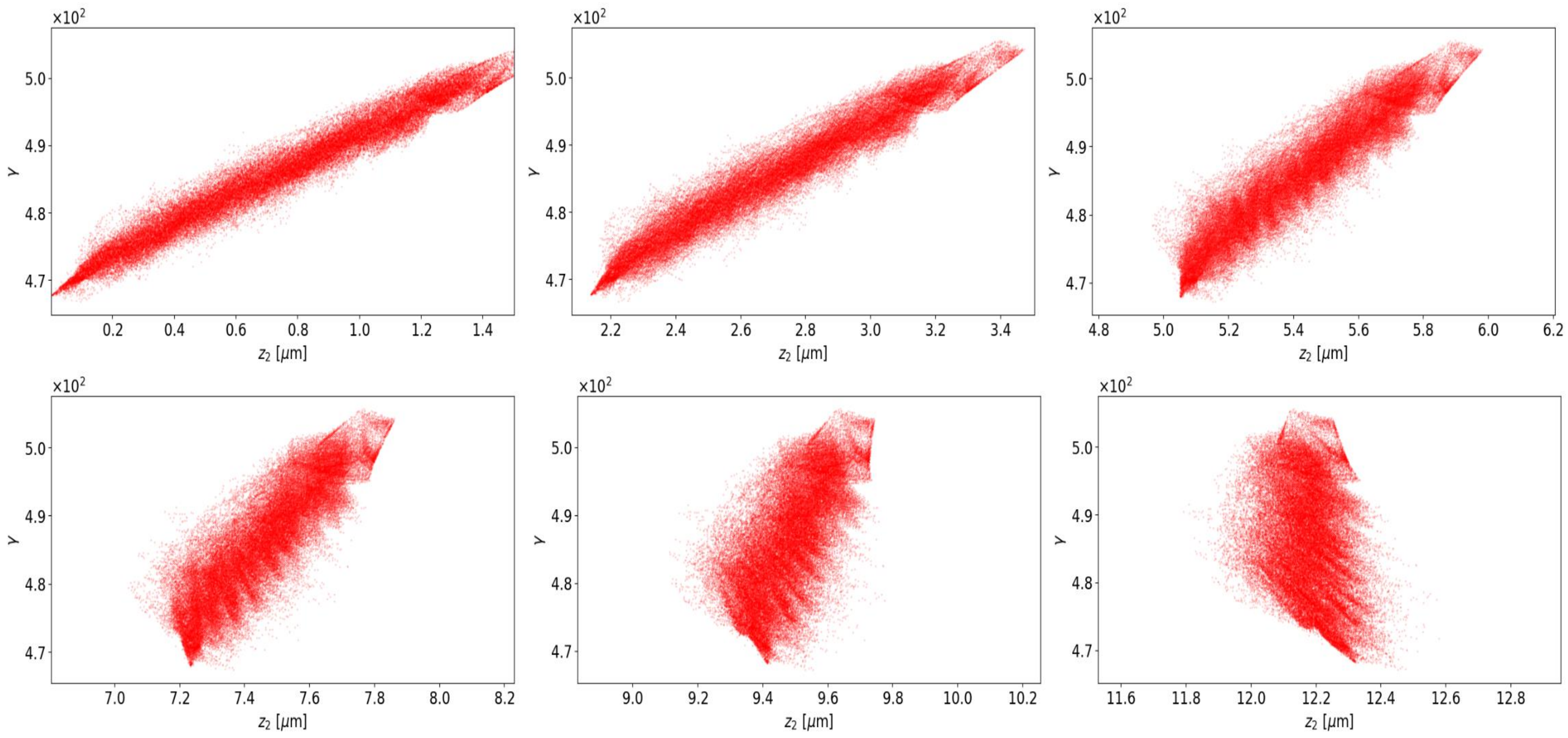

Fig.3 The electron beam evolution plotted for z=0m, 0.45m, 1.05m, 1.50m, 1.95m and 2.25m. The electron energy chirp causes the electron bunch to longitudinally compress in phase space and shorten as it propagates through the undulator. At saturation, z=1.95m, the electron bunch is only ~10 resonant radiation wavelengths long.

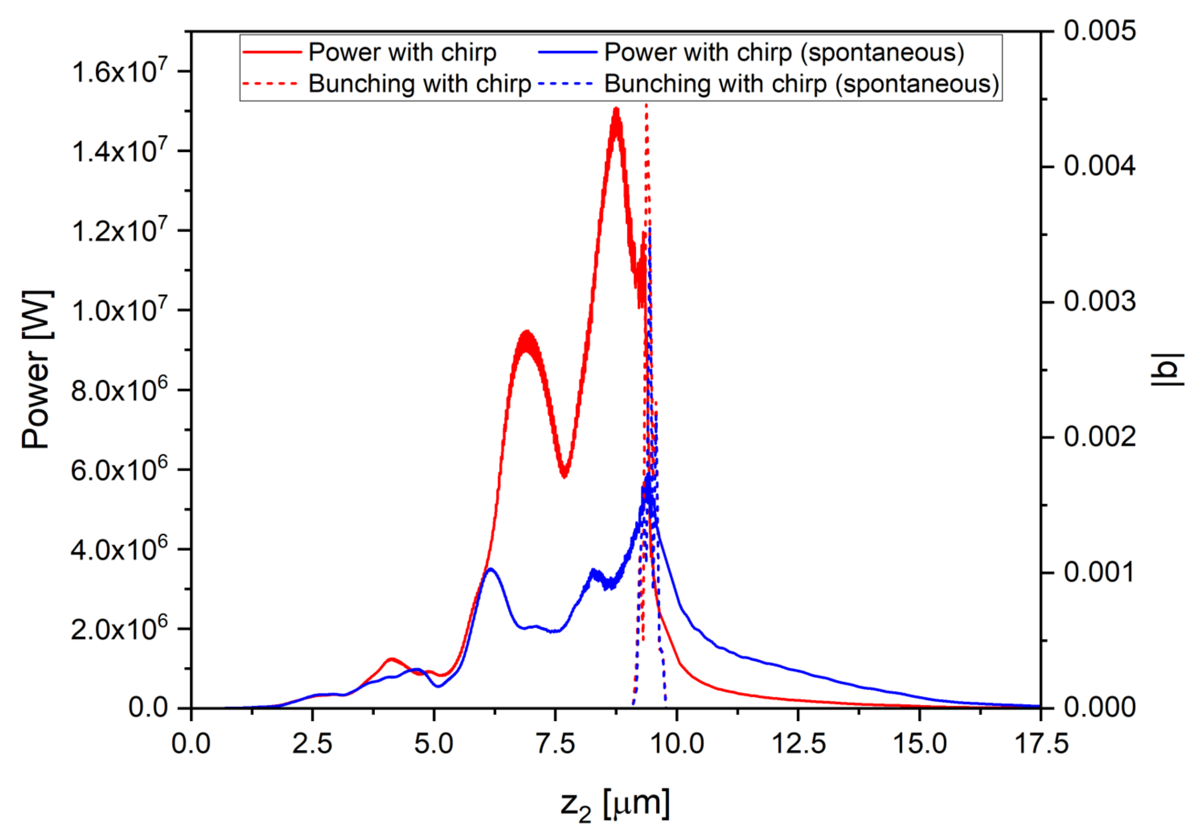

Fig.4 The radiation power profile (solid red) and the electron bunching parameter (dashed red) as a function of z_2=(ct−z) at z=z_{sat}=1.95m through the undulator for the energy chirped case and corresponding case for the FEL interaction 'switched off' (solid blue and dashed blue).

- The growth is not exponential but is **proportional to ~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 arises mainly from CSE.
- The FEL interaction can be *'switched off'* in the Puffin simulation by artificially de-coupling the electrons from the radiation field. The electrons then only emit spontaneous emission due to both shot-noise and CSE. The radiation energy growth from the chirped electron pulse, both with and without the FEL interaction, is shown in **Fig.5.** Here, there is no shortening of the electron pulse and the CSE emission is greatly reduced. The energy growth is 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 (**Fig.2**) increases quasi-linearly with distance through the undulator until z~1.2m. 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 [7,9].

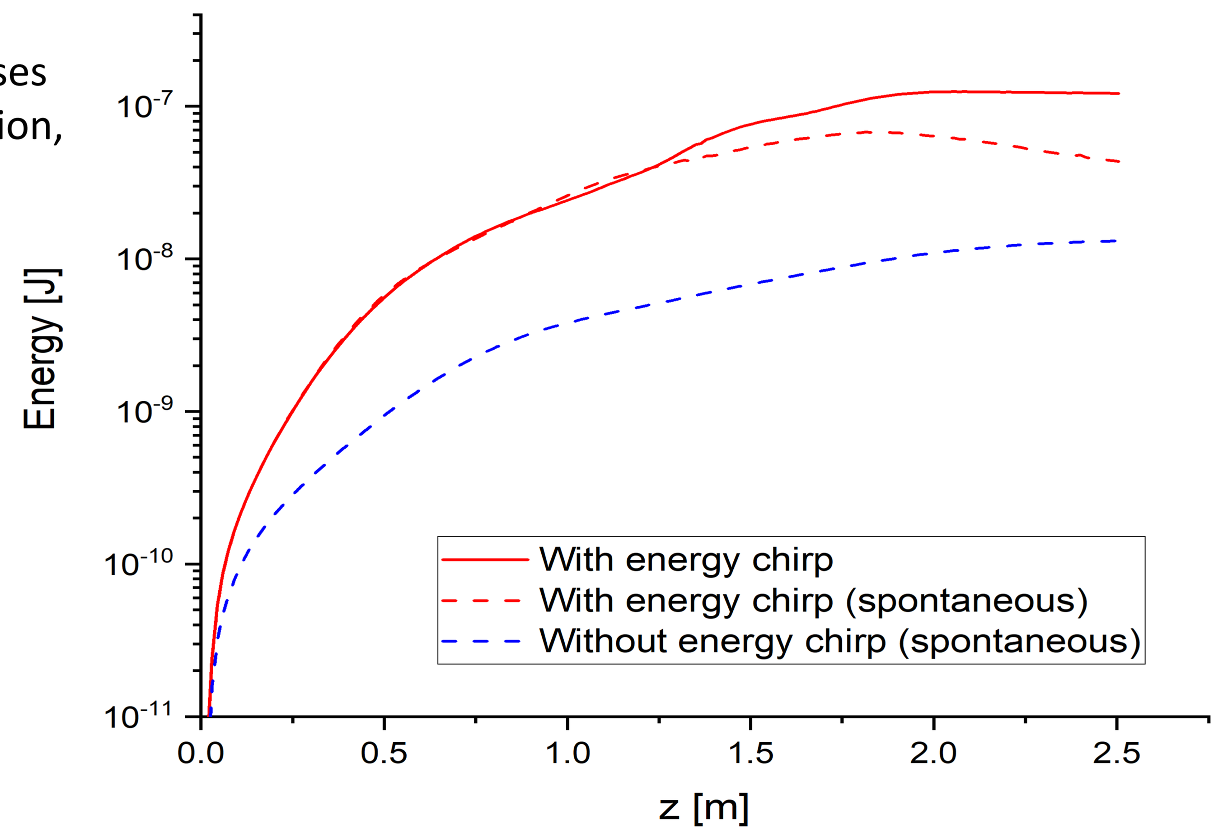

Fig.5 Radiation energy as a function of distance z through the undulator. Red curves are for the chirped pulse including (solid) the FEL interaction and (dashed) without the FEL interaction. The case without energy chirp or FEL interaction (blue) demonstrates an energy growth with a quasi-linear dependence with z, corresponding to shot-noise spontaneous emission without significant CSE contribution.

[1] Esary E et al 2009 Rev. Mod. Phys. 81 1229; [2] Hidding B, et al 2012, Phys. Rev. Lett. 108 035001; [3] Campbell L T and McNeil B W J 2012 Proc. FEL2012 (Nara, Japan); [4] https://github.com/UKFELs/FXFEL/ ; [5] https://github.com/UKFELs/JDF ; [6] McNeil B W J, Poole M W, and Robb G R M, 2003 Phys. Rev. ST Accel. Beam; [7] McNeil B W J, Robb G R M and Jaroszynski D A 1999 Opt. Commun. 165 65; [8] Campbell L T and McNeil B W J 2012 Phy. Plasmas. 19 093119; [9] McNeil B W J, Robb G R M and Jaroszynski D A 2000 Nucl. Inst .Meth. Phys. Res. A 445 72-76; [10] LT Campbell & BWJ McNeil, Phys. Plasmas 19, 093119 (2012)