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GENERATION OF VARIABLE POLARIZATION IN A SHORT WAVELENGTH FEL AMPLIFIER

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Abstract

To date, short wavelength Free Electron Laser amplifiers have generated linearly polarised radiation. For several important classes of experiment, variable polarisation is required. For example, in the wavelength range from 1.5 to 2.5 nm, light polarisation is important in characterising magnetic materials where measurements depend critically upon the handedness of the polarisation. It is therefore important that the polarisation does not fluctuate between measurements. In this paper, we study possible methods to generate variably polarised light and consider its shot-to-shot stability.

INTRODUCTION

Free Electron Lasers can now generate high intensity, fs pulses of linearly polarised radiation [1]. It is desirable to generate such radiation with circular polarization. It may be possible to modify existing facilities to generate circularly polarized light rather than build potentially expensive helical wiggler SASE FELs. Microbunched electron beams from existing planar wiggler SASE sources may be able to generate coherent circularly polarized radiation with similar powers to those of the existing planar wiggler FEL without extensive modification.

Conceptually, the simplest option is to inject microbunched electrons from a pre-saturated SASE planar wiggler FEL into a relatively short helical wiggler module. However, this may pose engineering challenges, and helical wigglers are significantly more expensive than planar wigglers. An alternative is the crossed planar wiggler scheme proposed in [2] and [3]. A secondary planar wiggler rotated 90° with respect to the first SASE wiggler will generate linearly polarized radiation perpendicular to that generated by the first wiggler. Ideally, the microbunched beam will radiate coherently and produce similar powers to that of the first wiggler in ~ 1.3 gain lengths [4] of the second wiggler. If a $\pi/2$ phase shift is supplied between the two wigglers the combined radiation of the 2 sources should sum to give circularly polarized light. However, since the second wiggler must be $\sim$ 1.3 gain lengths to produce 'perfect' circular polarization, the system can only be optimised for one resonant wavelength for a given set of beam parameters.

A modified crossed planar wiggler proposed in [5] and shown schematically in Fig. 1 may remove this constraint. By dumping the radiation from the first SASE wiggler and then using two wigglers of equal length rotated 90° with respect to each other, the powers generated by the micro-bunched beam in each of these wigglers can be made equal and the polarization controlled by a relative phase shift between the two. The polarization stability of this scheme has been analyzed in [6], where 3D GENESIS simulations were used to calulate the radiation fields from the two crossed wigglers.

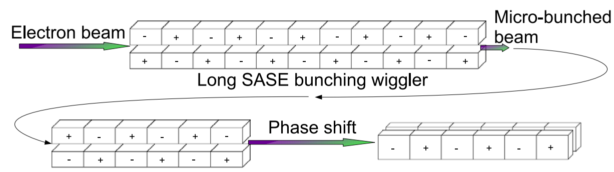

Figure 1: Illustration of the alterative crossed wiggler scheme from [5]

The unaveraged model presented in [7] describes a FEL with a variably polarised wiggler, and is capable of self-consistently describing the seperate transverse radiation fields through a common complex field. In addition, the model describes an extended radiation spectrum including significantly higher and lower frequency content simultaneously, subject to the Nyquist condition. The ability of this model to describe different radiation and wiggler polarizations accurately is discussed, and an example of how the crossed planar wiggler scheme can be simulated is shown with some preliminary results.

THE MODEL

Details of the derivation and scaling of the working equations may be obtained from [7] and are summarised here.

The FEL interaction is described by the coupled 3D Maxwell-Lorentz equations in a variable magnetic wiggler field defined as:

$$\mathbf{B}_w = \frac{B_w}{2}(\hat{\mathbf{f}} e^{-ik_w z} + c.c.) \tag{1}$$

where the unnormalized vector basis:

$$\hat{\mathbf{f}} = f_x \hat{\mathbf{x}} + i f_y \hat{\mathbf{y}} \tag{2}$$

is used to define a variable polarized wiggler field and where B_w is the peak magnetic field strength. Hence, f_x and f_y describe the strength of the wiggler magnetic field in x and y. The vector basis $\hat{\mathbf{f}}$ is un-normalized so that the RMS magnetic field $\bar{B}_w$ varies from $B_w/\sqrt{2} \le \bar{B}_w \le B_w$ as the wiggler changes from planar to helical.

The electromagnetic field is defined as:

$$\mathbf{E}(x,y,z,t) = \frac{1}{\sqrt{2}}\left(\hat{\mathbf{e}}\xi_0 e^{i(kz-\omega t)} + \hat{\mathbf{e}}^*\xi_0^* e^{-i(kz-\omega t)}\right) \tag{3}$$

with complex envelope $\xi_0(x,y,z,t)$ and the normalized vector basis $\hat{\mathbf{e}} = \frac{1}{\sqrt{2}}(\hat{\mathbf{x}}+i\hat{\mathbf{y}})$ is defined with $\hat{\mathbf{e}}\cdot\hat{\mathbf{e}} = \hat{\mathbf{e}}^*\cdot\hat{\mathbf{e}}^* = 0$ and $\hat{\mathbf{e}}\cdot\hat{\mathbf{e}}^* = 1$. Projecting the field onto $\hat{\mathbf{e}}^*$ gives:

$$E_\perp = \xi_0 e^{i(kz-\omega t)} = E_x - iE_y \tag{4}$$

where E_x and E_y are the field components in x and y, or in terms of the scaled units of the working equations:

$$A_\perp = A\exp(-i(\bar{z}_2/2\rho)) = A_x - iA_y. \tag{5}$$

Rewriting the complex envelope A with an explicit magnitude and phase $A = |A|e^{i\psi}$ gives

$$A_x = |A|\cos(\bar{z}_2 - \psi) \tag{6}$$

$$A_y = |A|\sin(\bar{z}_2 - \psi) \tag{7}$$

For constant $|A|$ and ψ, these fields describe a circularly polarised field. More generally, if $|A|$ and ψ are both functions of $\bar{z}$ and $\bar{z}_2$ they can describe any polarization. This is what happens in the code which solves numerically for $A_\perp$: the radiation amplitide, phase and polarization evolve self-consistently, both driving, and being driven by, the transverse electron current due to a variable wiggler polarization. Unlike other simulation codes, the radiation field polarisation is not fixed with respect to any transverse axis. To obtain the complex envelope required for a given polarization equation (5) is re-arranged to obtain the real and imaginary parts of the envelope in terms of A_x and A_y. It can then be shown that the magnitude and phase of the envelope vary as:

$$|A| = \sqrt{A_x^2 + A_y^2} \tag{8}$$

$$\tan\psi = \left(\frac{A_x\sin(\bar{z}_2/2\rho) - A_y\cos(\bar{z}_2/2\rho)}{A_x\cos(\bar{z}_2/2\rho) + A_y\sin(\bar{z}_2/2\rho)}\right) \tag{9}$$

for the given polarization.

COMPUTATIONAL SOLUTION

The code which solves the combined electron-field interaction is described in more detail in [7]. The partial differential equations describing the field and electron variable evolution are solved using a Fourier split-step integration method, where the first half-step solves field diffraction using Fourier transform methods, and the second half step integrates the driven electron and field equations using a Runge Kutte 4th order and finite element method. All computation is performed in parallel and memory usage is spread evenly across processors increasing code efficiency.

VARIABLE WIGGLER POLARISATION SIMULATION

A general elliptical wiggler field can be varied from a linear to a full helical polarization with the electron beam

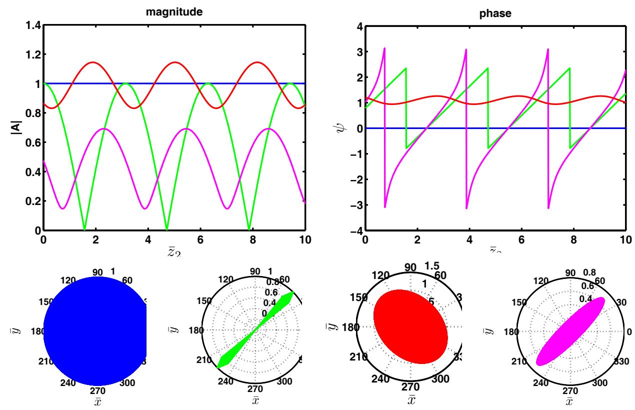

Figure 2: Illustration of how the complex envelope magnitude and phase vary to obtain different polarizations.

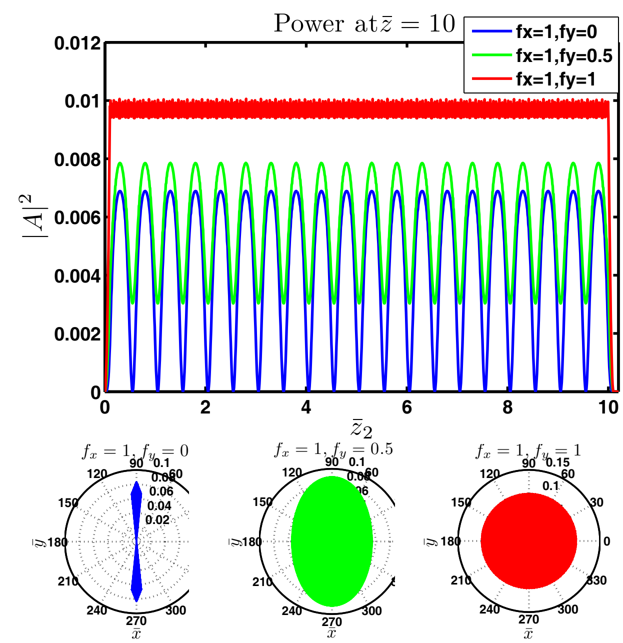

Figure 3: Example of different field polarizations as driven by electrons in planar, eliptical and helical wigglers as specified by f_x and f_y. The radiation polarization profiles are shown at the bottom, and the scaled powers on top.

having a corresponding transverse current. Simulations are now presented that demonstrate that the field and its polarization are driven consistently with such a variable transverse current.

In Figure 3 the x and y components of the radiation fields driven by a very short $\approx \lambda_r/10$ electron pulse propagating through three 20-period wigglers of different polarisation of are plotted. The electron pulse has a gaussian charge distribution and, being of sub-wavelength duration, behaves almost like a single high-charge particle emitting coherently. The self-consistent interaction of the field on the electrons was artificially switched off. The wiggler parameter $\bar{a}_w = 0.5$, so there is a relatively small harmonic content. The FEL parameter $\rho = 0.0796$. This simulation demonstrates that the electrons drive the correct field polarization via the complex field. Note that the scaled 'instantaneous power' $\propto |E_\perp|^2$, i.e. including the fast oscillatory field term, has been plotted. The sinusoidal amplitude of the electric field is evident in the planar and elliptical cases whereas the non-oscillatory ampliutide of the electric field in the helical case gives a continuous instantaneous power.

PRELIMINARY RESULTS FROM A CROSSED PLANAR FEL SYSTEM

Although the crossed planar wiggler scheme of [5] in principle allows tunable circular polarization in SASE, the electron bunching is initially noisy. Such bunching may impede the ability of this scheme to achieve good circular polarization. This is because the phase slippage induced to achieve the circular polarisation, even for relatively small wiggler lengths and phase shifts, may not allow good amplitude and phase matching of the electric fields to give the desired polarisation. A simulation with the unaveraged code to examine the effects of this is now outlined and preliminary results presented.

An electron pulse of 40 cooperation lengths is propagated through a long planar wiggler to just before saturation, approx 17.5 gain lengths. The FEL parameter was set to $\rho = 0.01$. This is larger than typical values for short wavelength SASE FEL's however it reduces the computational load and enables initial predictions and investigation of the principles to be made quickly.

The noisy radiation output and bunching is typical of the SASE process. A cold, flat top current distribution was used so that a large fraction of the beam evolves only from shot-noise. However, as this is an unaveraged code, CSE is generated at the edges of the beam, with that from the back developing into a superradiant spike. The front 15 cooperation lengths of the electron pulse have been untouched by superradiant SACSE spike evolution and have evolved only from shot-noise. To artificially remove CSE effects,

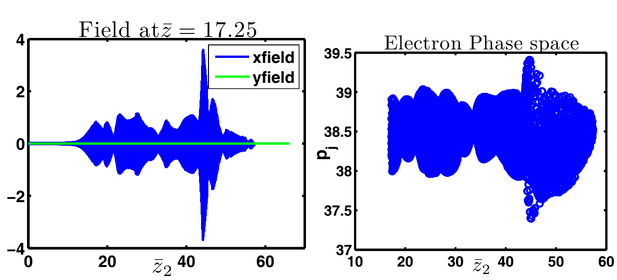

Figure 4: Simulation of the SASE bunching FEL. On the left is a plot of the x and y fields at the end of the wiggler. On the right is the electron phase space. Note the SACSE spike at $\bar{z}_2 \approx 42$. In the $\bar{z}_2$ frame the tail of the pulse is to the right and the head to the left. A section of the electron pulse from $\bar{z}_2 = 17.25$ to 32.25 which has evolved from noise only (no CSE) was selected for input into the crossed planar FEL.

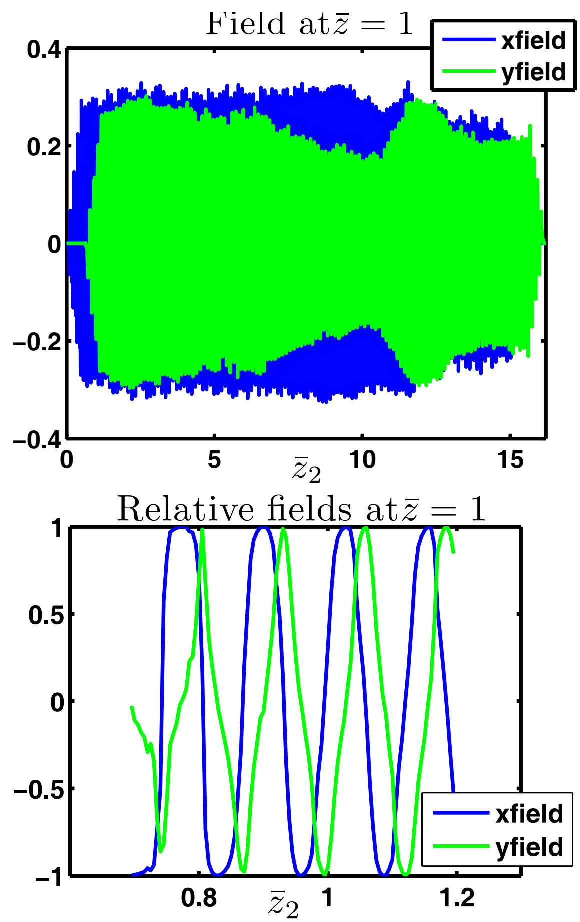

Figure 5: Simulation of the crossed planar FEL. The micro bunched electron beam has propagated to $\bar{z} = 1$. The wiggler polarization was switched from a planar in y to a planar in x and a $\pi/2$ phase shift added at $\bar{z} = 0.5$. The x and y fields are shown here, the bottom plot is enlarged to show the structure of the fields, and the magnitudes are scaled to the total magnitude of the radiation vector for ease of comparison.

this section only of the beam was selected for input into the two crossed planar wigglers with the remainder of the beam discarded.

The shortened beam was then injected into a combined cross wiggler a total of 1 gain length long. As the beam had been pre-bunched, high power radiation is emmitted in both wigglers sections. After one half a gain length the planar wiggler polarization was rotated by $\pi/2$, to change from a y to x polarized planar wiggler, and a $\pi/2$ phase shift was added to the electron beam.

Figure 5 shows the resulting transverse radiation fields. As this model is unaveraged the higher harmonics evolve self consistently and the odd harmonics of the planar wiggler are seen in Fig. 6. The waveforms in Fig. 5 show the fields in both planes are modulated, possibly by the harmonic content, which may adversely affect the generation of good circular polarization. The scaled instantaneous radiation power $|A_\perp|^2$ shows significant modulation indicat-

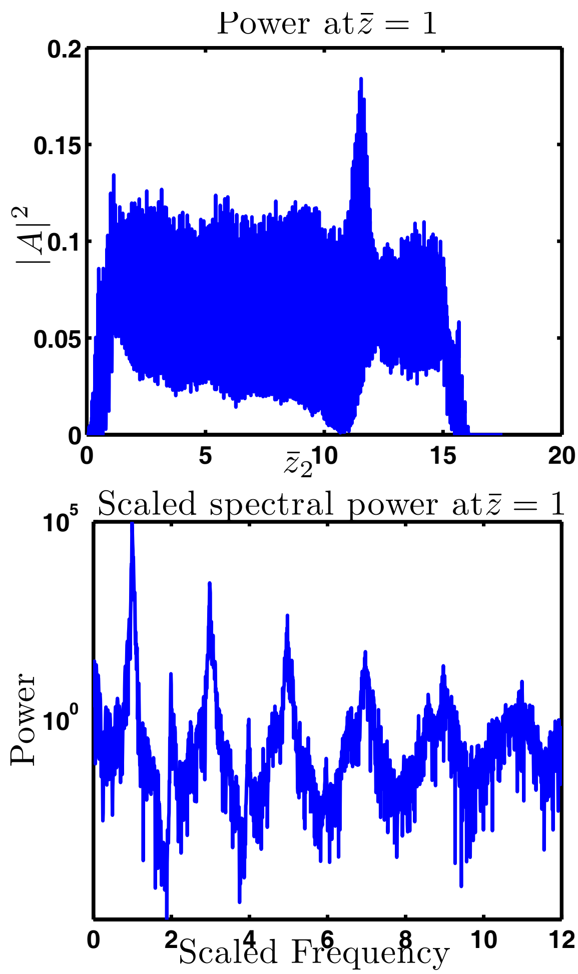

Figure 6: Simulation of the crossed planar FEL. On top is the scaled power, and the bottom shows the frequency content of the signal scaled to the frequency of fundamental.

ing that the degree of circular polarization of the radiation is quite poor. Also note that the amplitude of the y component of the radiation field is less than that of the x component. This may result from electron de-bunching in the first y polarized planar wiggler reducing power output in the second x polarised wiggler. Further optimisation may mitigate such effects.

CONCLUSION

The model presented here is a potentially powerful tool for investigating variable polarization effects in the FEL, allowing fully variably polarized wigglers and radiation fields to be modelled self consistently. The examples shown are 'work in progress' and, although rudimentary, demonstrate the potential of the code to investigate polarization phenomena in FEL physics. The example simulation of the crossed planar FEL is an initial step towards examining how the beam characteristics affect the final field polarization. The field polarization must now be described in a quantitative manner, for example via Stoke's parameters. The form of the transverse field components are written here in terms of the common complex field envelope. To determine the Stokes' parameters this description must now be related to the independently varying magnitude and phase of the transverse fields.

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