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UNAVERAGED SIMULATION OF A REGENERATIVE AMPLIFIER FREE ELECTRON LASER

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Abstract

A regenerative amplifier free-electron laser (RAFEL) design and simulation requires the modelling of both the electron-light interaction in the FEL undulator and the optical propagation within the cavity. An unaveraged 3D simulation was used to model the FEL interaction within the undulator using the Puffin code. This allows a broadband, high temporal-resolution of the FEL interaction. The Optical Propagation Code (OPC) was used to model the optical beam propagation within the cavity and diagnostics at the cavity mirrors. This paper presents the optical field conversion method between Puffin and the OPC codes and demonstrates the full model via a VUV-RAFEL simulation.

INTRODUCTION

When using an oscillator FEL at shorter wavelengths, such as UV and X-ray, the optical components used to create the cavity will be a limiting factor due to the absorption of the optical materials at shorter wavelengths, or due to a lack of tunability via e.g. Bragg reflections. The RAFEL uses the high-gain undulator and a *small* amount of feedback to obtain the system saturation. Hence, the RAFEL can use low reflectivity mirrors for the optical cavity and operate into the short wavelength regime [1]. An overview of RAFEL operation over a wide range of parameters in the 1D limit is given in [2].

Several 3D FEL codes, such as Genesis 1.3 [3], are used to model the FEL interaction based on the Slowly Varying Envelope Approximation (SVEA). However, Puffin [4] is an unaveraged FEL code without the SVEA approximation and does not use undulator period averaging of the electron trajectories. The resultant radiation field retains the fast-oscillating term and allows the modelling of broadband (few cycle radiation field) and more complex electron dynamics. This paper describes how the modelling of such behaviour can be achieved in a RAFEL.

Previously, Genesis 1.3 was used with the Optical Propagation Code (OPC) [5], to simulate a RAFEL in the VUV-FEL by running both codes sequentially [6]. OPC includes 3D mirror reflection and free-space propagation through the optical path of the cavity. OPC is used here to model the optical propagation inside the RAFEL cavity while the FEL interaction inside the undulator is modelled using Puffin.

This paper first describes the translation of the input/output optical field files between Puffin and OPC necessary for linking the two codes. A RAFEL design operating in the VUV at 100 nm is then described. The optical cavity was designed to satisfy the cavity stability condition and match the undulator length and the electron beam repetition rate.

FORMAT CONVERSION

The Puffin field data consists of 4D array data set in the HDF5 format with the dimension of (2, n_z, n_y, n_x), which is the two sets of 3D field data in space separated by the polarised orientation (x-polarized and y-polarized field). The n_z represents the data in the direction corresponding to the propagation of the field. For one-wavelength long data simulation, the output field from Puffin is a single period oscillation, as shown the example of the transverse Gaussian field in Figure 1.

The OPC field is described in two files. The first is the field data in the format of binary data in the Genesis '.dfl' field file format. Each point of data contains 8 bytes (64-bit) of binary data that represents the floating number, which can be dumped into a 1D array. The size of the product of the number of grid points in *x* and *y* etc, is contained in the second OPC parameter file containing the gridpoint parameters, number of slices in z etc. The transverse optical field profile data consists of two components of the complex number – real and imaginary parts, which interleave in the array by odd and even indices of the 1D data array. For the temporal information in the OPC data, the number of slices sets as the additional axis of the array corresponding to the z-direction of the optical propagation.

The Python conversion script starts by considering the envelope of the optical field from the analytical function, which includes real and imaginary parts of the sinusoidal function. For a simple plane wave, the real-valued radiation field that would be obtained from Puffin is written in Eq. (1)

$$A_{puffin}(\mathbf{r},t) = A_0(\mathbf{r},t)\cos\left(kz - \omega t + \phi(\mathbf{r},t)\right) \quad (1)$$

where A_{puffin} is the scaled radiation field with the amplitude of A_0, k is the radiation wave number, ω is the angular frequency of the radiation wave, and $\phi(\mathbf{r},t)$ is the phase of the field. The analytic signal will be used to translate the real-value field from Puffin into the complex representation of OPC field format using the Hilbert transform [7], which has the effect of shifting the phase of the original signal by $-\pi/2$. The Hilbert transform (denoted by a 'hat') of the original Puffin field can then be written in Eq. (2) as:

$$\hat{A}_{puffin}(\mathbf{r},t) = A_0(\mathbf{r},t)\sin\left(kz - \omega t + \phi(\mathbf{r},t)\right) \quad (2)$$

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The envelope itself can be constructed from the modulus of the analytic signal composing with the original field and its Hilbert transform, which corresponds to the OPC field format, which is written in the complex notation in Eq. (3).

$$\begin{aligned}\tilde{A}_{opc}(\mathbf{r},t) &= A_{puffin}(\mathbf{r},t) + i\hat{A}_{puffin}(\mathbf{r},t)\\ &= A_0(\mathbf{r},t)\exp\left[i(kz-\omega t+\phi(\mathbf{r},t))\right]\end{aligned} \tag{3}$$

In this way, $A_{puffin}(\mathbf{r},t) = \mathrm{Re}\left(\tilde{A}_{opc}(\mathbf{r},t)\right)$. Hence, the real-value Puffin field data at each grid point will be transferred directly to the real part grid points of the OPC data and the phase-shifted part of the Puffin field, via its Hilbert transform, will be used as the imaginary part of the OPC field. The example of the conversion process is shown in Fig. 1.

For the backward conversion from OPC into Puffin, the process simply extracts the real part of the OPC data file and assumes the number of grid points etc in the OPC parameter has not changed. The script converts to HDF5 format.

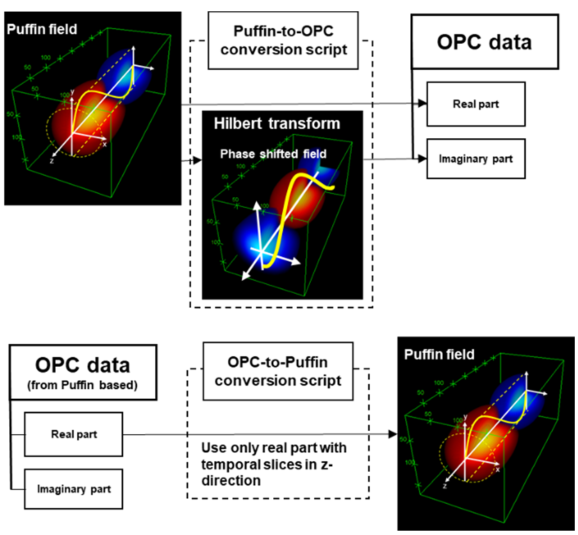

Figure 1: The form of the Puffin output field and the conversion method into the OPC field format. Top: Puffin-to-OPC and Bottom: OPC-to-Puffin format conversion.

DESIGN PARAMETERS

100 nm Wavelength FEL

The VUV RAFEL simulations are for a 100 nm wavelength. All parameters are taken from CLARA conceptual design report [8], with an electron energy of 250 MeV and peak current 400 mA. The undulator length for RAFEL operation, using only one-third of the SASE saturation undulators consists of five 1.25m modules comprised of 29 undulator periods of λ_u = 27.5 mm and a gap between modules of ~ 0.45 m for quadrupole focussing etc.

Optical Cavity

The RAFEL system required a small feedback optical cavity. The cavity length is set to 17.5 m to match the 8.5 MHz bunch repetition rate. The optical cavity design takes the output field at the undulator exit and must propagate it to the undulator entrance to seed a new incoming electron pulse. The radiation field is focussed to the undulator entrance to maximise the overlap between the radiation field and electron beam. The layout of the undulator with the optical cavity is shown in Fig. 2. The first mirror of radius of curvature 12.32 m (so that its focal length is 12.32/2 = 6.16m) has been placed 8.0 m away from the undulator exit with a 2.0 mm diameter out-coupling hole. The second mirror at the undulator entrance has a radius of curvature of 9.98 m. , i.e. a stable resonator. The RAFEL operation should then reach saturation within a few cavity round-trips [6].

The system is designed to use mirrors with the reflectivity in a range of 20% to 40% to cover a sufficiently broad range of wavelengths around 100 nm. The relatively high reflectance at these wavelengths can be obtained from using Boron films deposited coating [9].

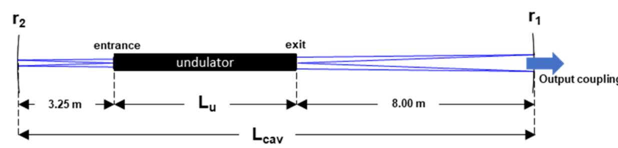

Figure 2: Schematic of the RAFEL used in the simulation. The blue line shows the ray-tracing of the propagating optical beam inside the cavity.

EXAMPLE SIMULATION

To test the simulation set up, a simple setup uses a single wavelength in a periodic mode of the Puffin simulation. This is equivalent to the steady-state approximation. The simulation starts in the first pass using the shot noise of electron beam, the main input of the system and the undulator lattice files required by Puffin. The radiation field output from the first pass at the undulator exit is then converted from Puffin format to OPC format as described above. The grid size of two codes must be matched at the beginning of the simulation setup. The OPC main input file contains all of the optical path and the optical elements, i.e. mirrors. The converted field then propagates using OPC through the optical cavity system via free-space propagation and the two mirrors - the first mirror has a hole out-coupling and the second mirror reflects the light to the undulator entrance. The propagated field at the undulator entrance is then converted from OPC field format into Puffin format and used as the radiation seeding in the next pass via the Puffin main input file. The process runs sequentially, as shown in Fig. 3.

The simulation output of the optical field at different points through the cavity is shown in Fig. 4. The integration of using Puffin and OPC still contains the fast-oscillating term of the radiation field that shows the resulting wavefront of the propagating fields. The diverging beam at the undulator exit due to diffraction and the converging beam at the reflective mirrors can be seen.

The RAFEL operation can be analysed via the input seeding from the optical cavity at the undulator entrance

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and the output field after passing through an FEL undulator at the exit. The result shows there is sufficient optical feedback to achieve saturated RAFEL operation a mirror reflectivity of 20% for both mirrors and an upstream mirror hole out-coupling of 2.0mm. The RAFEL system saturates at around five round-trips as seen from the power output of Fig. 5.

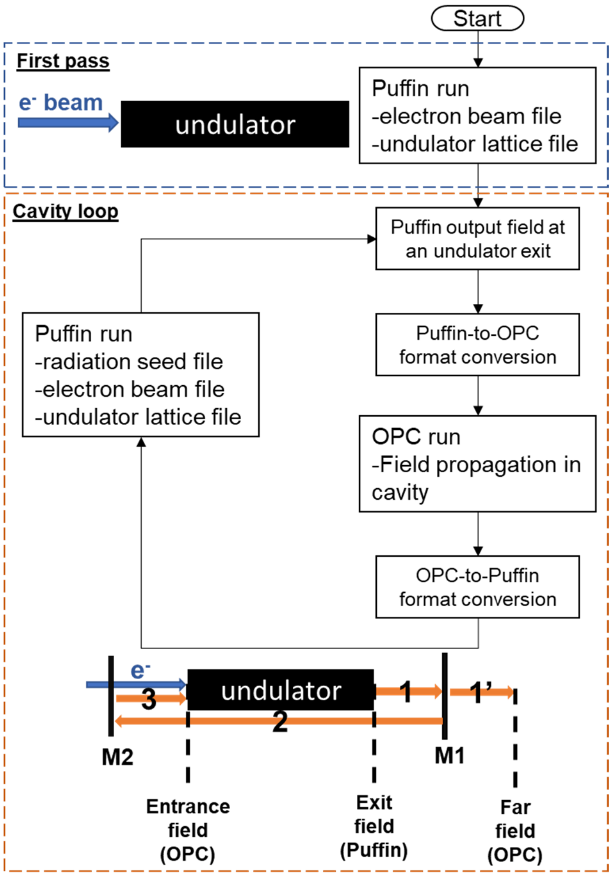

Figure 3: The diagram shows the flow chart of the RAFEL simulation, including the first pass, conversion script, and the cavity loop which is a simple Bash shell script. (1) The first propagation using OPC from the undulator exit to mirror-1 (M1) with a hole out-coupling and the far-field diagnostic point (1'). (2) The second propagation from a reflected optical beam at M1 to mirror-2 (M2). (3) The third propagation from M2 to the undulator entrance as the next loop radiation seeding.

CONCLUSION

The Puffin and OPC simulation codes have been developed for use together for FEL oscillator simulations. Conversion scripts were developed to enable radiation field transfer between the two codes. And demonstrated with a steady state, single wavelength periodic mode model of a VUV-RAFEL design. This will enable the development of FEL modelling of potential ultra short-pulse, broadband simulations in the future.

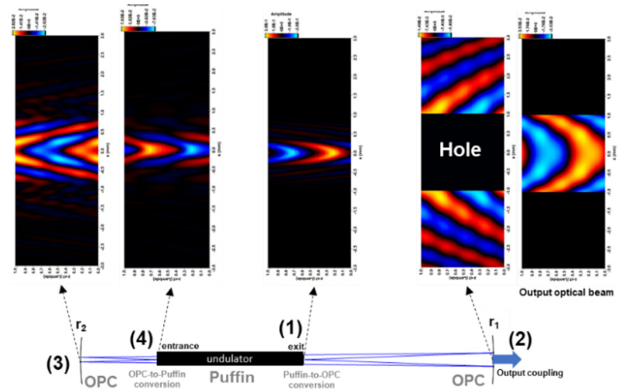

Figure 4: The schematic shows the optical beam of one-wavelength (periodic-mode) at the difference diagnostic positions of the RAFEL system. The Red and Blue colours show the positive and negative values of the electric field, respectively. Point (1) is the diverging optical beam at the undulator exit propagates to (2) at the mirror-1 with a hole out-coupling. Part of the beam is then reflected back as a converging beam to the mirror-2 at point (3), and then focused to point (4) at the undulator entrance.

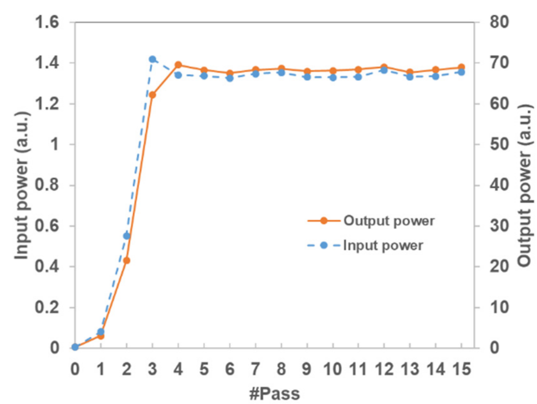

Figure 5: The input and output power at the undulator entrance and exit, respectively. The plot shows the system saturation at around five round-trips of propagation.

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