RECENT UPGRADE TO THE FREE-ELECTRON LASER CODE GENESIS 1.3

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Abstract

The time-dependent code GENESIS 1.3 has been modified to address new problems in modeling Free-Electron Lasers. The functionality has been extended to include higher harmonics and to allow for a smoother modeling of cascading FELs. The code has also been exported to a parallel computer architecture for faster execution using the MPI protocol.

INTRODUCTION

Numerical codes have become an integral component to study and design Free-electron Lasers worldwide. The underlying theory is rather complex and allows analytical solution only under approximations. The level of complexity increases with a more refined and realistic model of the FEL which include effects such as electron beam misalignment, undulator field errors, and start-up from spontaneous radiation. In addition new concepts of cascading Free-electron Lasers are studied, which are following a rather inhomogeneous set-up as compared to the 'simple' single undulator of a SASE FEL.

Several numerical codes exists to model FELs. In this paper we present the current status of the time-dependent, three dimensional code Genesis [1] and report on the current improvement to address the modeling of cascading FELs as well as utilizing parallel computer architecture.

MODELING OF HARMONICS

For the implementation of harmonics in the code, several methods have been considered, which can couple the field of higher harmonics to the electron beams [2, 3]. The dominant coupling mechanism arises from the betatron motion of the electron. In comparison, the coupling of the other mechanisms are weak and they have not been implemented in Genesis.

The electron motion in a planar undulator is given by:

$$\beta_x = \frac{K}{\gamma}\cos(k_u z) + \hat{\beta}_x, \tag{1}$$

$$\beta_y = \hat{\beta}_y, \tag{2}$$

$$\begin{aligned} \beta_z &= 1 - \frac{1+K^2/2}{2\gamma^2} - \frac{\hat{\beta}_x^2 + \hat{\beta}_y^2}{2} \\ &\quad - \frac{K^2}{4\gamma^2}\cos(2k_u z) - \frac{\hat{\beta}_x K}{\gamma}\cos(k_u z), \end{aligned} \tag{3}$$

where K is the unitless undulator parameter, k_u the undulator wavenumber, γ the electron energy. The velocities, indicated by the hat, are referring to the betatron motion, which is slow compared to the fast wiggle motion. Because the electrons perform a longitudinal oscillation, they cannot stay in optimum phase with the co-propagating radiation field and the coupling to the fundamental is reduced. On the other hand the longitudinal oscillation is the reason for the coupling to higher harmonics.

The change in the electron energy for a planar polarized radiation field of the nth harmonics with wavenumber nk_0 and frequency $n\omega_0$ (k_0, ω_0 are the wavenumber and frequency, respectively, of the fundamental mode) is given by:

$$\begin{aligned} \frac{d}{dz}\gamma &= \frac{eK}{2mc\gamma}\Re\mathrm{e}\left(E_n e^{-ink_0 z + in\omega_0 t}\left[e^{ik_u z} + e^{-ik_u z}\right]\right. \\ &\quad \left. \times e^{i\xi\sin(2k_u z) + i\chi\sin(k_u z)}\right) \end{aligned} \tag{4}$$

with $\xi = nk_0K^2/8\gamma^2k_u$, $\chi = nk_0\hat{\beta}_x K/\gamma k_u$, and E_n the complex value field amplitude of the nth harmonic. Eq. 4 can be simplified by using the identity $\exp(ia\sin b) = \sum J_j(a)\exp(ijb)$ and the introduction of the ponderomotive phase $\theta = (k_0 + k_u)z - \omega_0 t$. The energy change is then

$$\begin{aligned} \frac{d}{dz}\gamma &= \frac{eK}{2mc\gamma}\Re\mathrm{e}\left(E_n e^{-in\theta}\left[e^{i(n-1)k_u z} + e^{i(n+1)k_u z}\right]\right. \\ &\quad \left. \times \sum_{j=-\infty}^{\infty} J_j(\xi)e^{ij2k_u z}\sum_{m=-\infty}^{\infty} J_m(\chi)e^{imk_u z}\right). \end{aligned} \tag{5}$$

When averaged over an undulator period most terms are not resonant except those, which are fulfilling the condition

$$n \pm 1 + 2j + m = 0 \quad .$$

Genesis 1.3 assumes that the argument χ is much smaller than unity and therefore m is restricted to the values of -1, 0, and 1. The corresponding Bessel functions are expanded into Taylor series up to first order [4]. The resulting coupling to the radiation field are expressed by coupling factors. They are then

$$JJ_n = (-1)^{\frac{n-1}{2}}[J_{\frac{n-1}{2}}(\xi) - J_{\frac{n+1}{2}}(\xi)] \tag{6}$$

for odd harmonics and

$$JJ_n = (-1)^{\frac{n-2}{2}}\frac{\chi}{2}[J_{\frac{n-2}{2}}(\xi) - J_{\frac{n+2}{2}}(\xi)] \tag{7}$$

for even harmonics. Note that for even harmonics the coupling factor is different for each electron and depends on its current angle in the betatron trajectory ($\chi \propto \hat{\beta}_x \approx x'$).

The coupling factor can be alternatively derived from the Maxwell equation in its par-axial approximation.

Though a helical undulator can couple to the second harmonic in a fashion similar to the coupling to even harmonics in a planar undulator, that feature is not implemented. The main argument to exclude it is that the helical mode within Genesis assumes an equal field amplitude in bother planes. The coupling to the second harmonics depends on the current alignment of the electron beam. A fully aligned beam tends to suppress the emission because any given coupling factor of an electron, which scales with the current divergence from the undulator axis, is compensated by electrons moving in the opposite direction. However it is not the case when the beam centroid undergoes a betatron oscillation. Most electrons are propagating under the same angle with respect to the undulator axis and the emission adds up constructively (all coupling factors have the same sign). If the beam is misaligned in the horizontal plane the emission on the second harmonics would be predominantly planar which is in conflict with Genesis 1.3 methods of modeling helical undulators with equal field amplitude in both planes.

The original code allows the same subroutines to be reused for calculating the higher harmonics as long as the correct wavenumber and coupling factor is used for the harmonic under consideration. However, Genesis 1.3 is written in FORTRAN 77 standard and the lack of object oriented algorithm requires an increased level of bookkeeping because the fundamental and all harmonics are stored in the same array to provide optimum memory efficiency. In addition, the memory demands for time-dependent simulations scale with the number of harmonics, and can cause for large harmonic numbers to overflow the pre-defined array holding the slippage field. This can be avoided by temporarily storing the slippage field in an external file though it comes with a penalty of increased computational time due to the slower read and write access to a file as compared to memory.

CASCADING SIMULATIONS

To support the study of cascading FELs, such as the HGHG FEL [5], it is often required to export the particle and field distribution, and then to reimport them after some processing and manipulation. These files follow the internal format of the electron beam and radiation beam within Genesis. The user can control via the main input deck if a particle or field distribution is dumped at the end of a run or imported at the beginning of it. For importing, Genesis skips the internal generation of the particle or field distribution and takes the distribution directly from the file. The files have to conform with the quiet loading mechanism and the correct shot noise statistic [6] to avoid systematic errors in the following run.

To streamline the modeling of HGHG FELs, Genesis supplies some pre-processing routine to the electron distribution after it has read the distribution from the file but before the actual simulation has started.

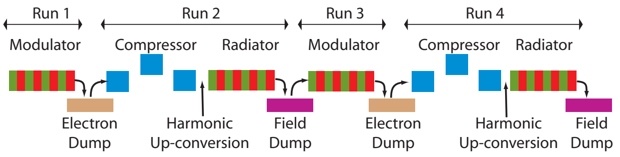

Figure 1: Flow diagram of Genesis for simulating 2 stages of a cascading HGHG FEL.

One feature is to convert the particle distribution to a higher harmonics. It is mainly the transformation $\theta \rightarrow n\theta$ which converts the nth harmonic from the input file to the new fundamental. In this process harmonics below n are eliminated as well as higher harmonics which are not integer harmonics to the nth harmonic. A second support function is to supply a transformation to the electron beam prior to a possible harmonic up-conversion. The user can choose a generic 4 magnet chicane by defining the magnet field strength and length as well as the drift space between, before and after the magnets. For more complex beam lines the entire R-transport matrix can be defined in the main input deck, which is conform to the standard notation of tracking programs using a 6 dimensional phase space vector $(x, x', y, y', s, \delta p/p)$. The transport matrix can be derived from other programs or analytical calculations.

Fig. 1 shows the program flow of a multi-stage HGHG simulation. In the first run, the modulator, the energy modulation is imprinted and the particle distribution is dumped. The undulator of the next stage is tuned to a harmonic. At the beginning of the second run the particle distribution is imported, transported through a dispersive magnet chicane and then up-converted to the harmonic under consideration. At the end the radiation field is saved and re-imported in the 3rd run. Run 3 and 4 are similar to the first two runs. Note that this is one possible way to address cascading HGHG simulation. It can be more self-consistent when, at each step, both the radiation field and the electron beam, are carried over to the next stage. The fresh-bunch method (not shown in Fig. 1) would require to shift the particle distribution with respect to the field profile.

It has to be noted that an external program has been developed which tracks the radiation field through an optical beam line (e.g. optical cavity) [7]. Scripts can also call both programs in alternation to model FEL oscillator simulations.

MODIFICATION FOR PARALLEL COMPUTER ARCHITECTURE

To compensate for long execution times of time-dependent simulations at short wavelength, the code has been modified to support parallel computer architectures, using the MPI protocol [8]. Steady-State simulations of a single slice typically takes less than 5 mins and there isn't

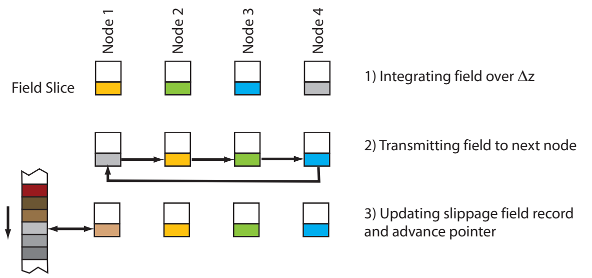

Figure 2: Management and transmission of the radiation field in a time-dependent simulation with a parallelized implementation of Genesis.

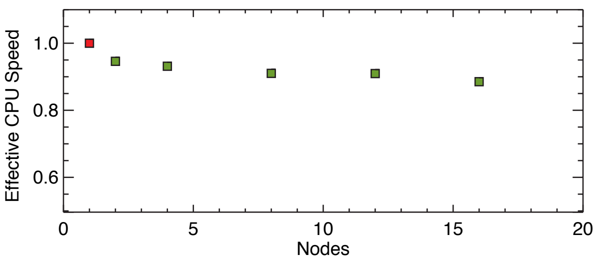

Figure 3: Effective CPU speed vs. number of processes. All values are normalized to the single node result which is the single processor version of Genesis.

any need to break-up the core algorithm of Genesis to support parallel computation on this basic level. Instead the code only benefits from a parallel architecture if more than one slice is simulated. This is the case for a parametric scan over a given input parameter and for time-dependent simulation. The MPI-implementation of the scan feature of Genesis is straightforward because there is no communication between the nodes during the tracking of the electron slice through the undulator.

For time-dependent simulations in the standard version of Genesis, a single slice is tracked through the undulator while slices of the radiation field slip into the region of the electron slice, interact with it and slip out. At the end of the undulator, the electron slice is discarded and a new slice ahead of the old one is generated. The slippage field, which has seen the interaction with the previous slices, is used again to slip into the region of the new electron slice. This algorithm allows Genesis to sequentially progress through the electron beam, starting from the tail and advancing towards the head.

In the parallel implementation, the nodes are configured in an open one dimensional topology where each node has only two neighbors except for the first and last node on this grid. At each step, when then radiation field is advanced, all nodes are sending their field information to the next higher neighbor, except for the last node which sends the field information to the first node. To complete the cycle the first node saves the received field to the updated slippage field record and replaces it with a new slice from that record. *De facto* it works similar to the stand-alone version except that now blocks of electron slices are tracked through the undulator instead of a single slice. Fig. 2 shows the information exchange for time-dependent simulation.

The chosen implementation requires a very symmetric parallel computer because all nodes are synchronized with each other when the radiation field is exchanged among them. Faster nodes are running idle until each node has finished its calculation.

Fig. 3 shows the efficiency of the parallel version of Genesis as a function of the number of nodes. The reference case is the stand-alone version of Genesis, indicated by the red marker in the plot. There is a systematic loss of CPU speed because the parallel version of Genesis has to transmit the field information to neighbor nodes in addition to the actual calculation. This degradation in its efficiency depends on the specific case to be simulated and can be as large as 50% for long wavelength FELs with a frequent exchange of the slippage field. The case, presented in Fig. 3, is based on the LCLS [9] parameter set with only a reduction of about 5%. Beside this systematic shift in the CPU speed there is a growing degradation with an increasing number of processors, caused by the accumulation of load imbalances on the nodes (note that Genesis synchronizes the execution with each exchange of the radiation field) and the growing load on the network.

CONCLUSION

The time-dependent simulation code Genesis 1.3 has been updated and allows modeling of harmonics in the radiation field, and of cascading FELs. To enhance the performance, the code has been exported to a parallel computer architecture. The source code and additional information can be downloaded from the Genesis website `http://pbpl.physics.ucla.edu/~reiche`.

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