

COUPLING MODULATOR SIMULATIONS INTO AN FEL AMPLIFIER FOR COHERENT ELECTRON COOLING*

I.V. Pogorelov[†], G.I. Bell, D.L. Bruhwiler,
B.T. Schwartz, S.D. Webb, Tech-X Corporation, Boulder, CO, USA
V.N. Litvinenko, G. Wang, Y. Hao, BNL, Upton, NY, USA

Abstract

Next-generation ion colliders will require effective cooling of high-energy hadron beams. Coherent electron cooling (CeC) can in principle cool relativistic hadron beams on orders-of-magnitude shorter time scales than other techniques [1]. Particle-in-cell (PIC) simulations of a CeC modulator with the parallel VORPAL framework generate macro-particle distributions with subtle but important phase space correlations. To couple these macro-particles into a 3D simulation code for the free-electron laser (FEL) amplifier, while retaining all details of the 6D phase space coordinates, we implemented an alternative approach based on particle-clone pairs [2]. Our approach allows for self-consistent treatment of shot noise and spontaneous radiation, with no need for quiet-start initialization of the FEL macro-particles' ponderomotive phase. We present results of comparing fully 3D amplifier modeling based on the particle-clone approach vs GENESIS [3] simulations where distribution of bunching parameter was used as input.

QUIET START ALGORITHM IN GENESIS

It is well known that randomly distributed macroparticles yield artificially strong spontaneous radiation in FEL simulation. If N_{mp} macroparticles are used to simulate a beam that consists of N_e physical electrons, shot noise goes up by a factor of $(N_e/N_{mp})^{1/2}$, and the power of spontaneous radiation is amplified by a factor of N_e/N_{mp} compared to the physical beam. One solution to this problem is to use a special seeding of macroparticles that comprise the initial distribution. GENESIS (as well as GINGER [4]) use for this purpose an algorithm due to Fawley [5]. If the fundamental wavelength λ_0 at which lasing will occur is known, $2M$ macroparticles are seeded at equal intervals within λ_0 (one $2M$ -tuple per original macroparticle). As shown in [5], with zero initial bunching one recovers correct spontaneous radiation through the M^{th} harmonic of the λ_0 . Physical shot noise can then be matched by introducing appropriately chosen amount of bunching, which is done by perturbing the initial phases of the $2M$ macroparticles around their equispaced locations.

* Work supported by the DOE Office of Science, Office of Nuclear Physics, grants No. DE-FG02-08ER85182 and DE-SC0000835, including the use of NERSC under contract No. DE-AC02-05CH11231, and by the Office of Basic Energy Sciences grant No. DE-SC0007576.

[†] ilya@txcorp.com

MACROPARTICLE-CLONE MODEL

FEL amplifier simulations that rely on the approach outlined in the previous section, as it is implemented in GENESIS, result in an essentially 1D coupling of the 3D electron density perturbation from the modulator. Given our interest in fully 3D FEL amplifier simulation that captures details such as coherent response to electron perturbations, full transverse beam size, etc, it is necessary to enable a direct use of VORPAL particle coordinates from the δf simulations of the modulator [6] (as opposed to generating a macroparticle distribution from the bunching factors inferred from VORPAL output). Doing so requires an alternative approach to controlling shot noise. We will use for this purpose an approach first proposed by Litvinenko [2]. The idea is to introduce positron-like clones in addition to electron-like macroparticles and to do this in such a way that an ensemble of electron-'positron' pairs reproduces exact statistical properties of the spontaneous radiation of the real beam.

In the macroparticle-clone (MP/C) approach, [the weight and] charge of macroparticles Q_{mp} and clones Q_{cl} are set as

$$Q_{mp} = e \frac{n_{np}}{2} \left(1 + \frac{\alpha}{\sqrt{n_{np}}} \right) \quad (1)$$

and

$$Q_{cl} = -e \frac{n_{np}}{2} \left(1 - \frac{\alpha}{\sqrt{n_{np}}} \right) \quad (2)$$

where the number of electrons per macroparticle $n_{mp} = N_e/N_{mp}$ is the ratio of the number of electrons in the beam N_e and the number of simulation macroparticles N_{mp} . Parameter α that appears in the above expressions for Q_{mp} and Q_{cl} is used to control the amount of shot noise in the input distribution. In two cases of interest, with $\alpha = 1$ one obtains physically correct shot noise, while setting $\alpha = 0$ results in no initial shot noise. "Positron" clone macroparticles are created for each "electron" macroparticle, with precisely the same initial phase space coordinates. In the absence of FEL interaction (and with the sign of magnetic field switched), clone trajectories are identical to those of electrons, their radiation cancelling each other. FEL interaction will result in separation of "electrons" and "positrons"; this bunching leads to induced radiation in the FEL. Induced radiation for the fundamental wavelength λ_0 and its odd harmonics is the same for the macroparticles and clones. When $\alpha = 1$, randomly distributed N_{mp} pairs of macroparticles and their clones will have the same statistics, the same spectrum, and the same power of sponta-

neous radiation as $N_e = N_{mp}n_{mp}$ randomly distributed electrons [2].

One shortcoming of this approach is that it is only applicable to odd harmonics of the fundamental mode. Correct treatment of even harmonics requires greater care. This, however, is not a problem for a short wavelength SASE FEL planned for the CeC experiment which is based on a helical wiggler and in which the gain length comprises many wiggler periods. In this case, only odd harmonics are present in the on-axis radiation [7]. To reiterate, the key advantage of the MP/C model for our purposes is that it allows for direct 3D coupling from the modulator distribution into the FEL amplifier.

IMPLEMENTATION AND BENCHMARKING

We implemented the approach of [2] in a modified version of GENESIS, to which we gave a working title EVOLUTION. As already mentioned, using particle-clone pairs should allow one to correctly reproduce the statistics, spectrum, and power of spontaneous radiation in 3D, time-dependent FEL simulations. Our verification and benchmarking efforts aim to confirm that this is indeed the case for the algorithm implementations in EVOLUTION. EVOLUTION reads in a 6D phase space distribution and replaces original macroparticles with pairs of clones, one of which is positron-like and the other electron-like in regard to their longitudinal dynamics. The weights of particles forming a clone pair are given by Eq-s 1 and 2. Noise can be varied by changing alpha from the default $\alpha = 1$ value (for which the physically correct amount of the shot noise is obtained). Transverse dynamics is identical for the two types of particles forming a clone pair, while the response to the longitudinal component of the EM field is that of oppositely charged particles. We have not yet implemented variably-weighted clones.

We significantly re-worked the GENESIS I/O interface, so that in EVOLUTION the standard GENESIS procedure of replacing the longitudinal distribution with internally generated distribution is bypassed. Instead, for every macroparticle in the input distribution, a pair of clones is produced (one clone being electron-like, the other positron-like). Unlike in GENESIS, slices in EVOLUTION are created such that they cover the entire bunch without overlap or gaps between the slices. The number of particles in a given slice is not forced to be equal to a number that is the same for all slices; instead, the number of clone pairs is the same as the number of macroparticles in the input distribution that happen to fall within a given slice. The tracking and radiation field computation routines have been changed so that the transverse dynamics is identical for the two types of clones, while the $d\gamma/dz$ is opposite for the positron- and electron-like clone particles in every pair.

We employed two types of verification and benchmarking tests for the newly implemented particle-clone simulation capabilities. In the first group of tests, we bench-

marked the results of simulations of SASE FEL in the linear high gain regime with EVOLUTION against the results produced with the original version of GENESIS in the same physical setting. In the second group of tests, which are currently in progress, we focus on the statistical properties of radiation from a SASE FEL operating in a linear mode, comparing EVOLUTION results to theoretical model predictions of Saldin *et al.* [8]. In what follows, we give a brief discussion of this benchmarking work.

Initial testing was performed with a quiet-start initial distribution, so as to make sure that no lasing occurs when shot noise is zero. This seems like a trivial case, but it helped to identify and understand many unexpected (to us) details of how GENESIS creates the initial distribution. In EVOLUTION, we bypass most of these special procedures, resulting in simpler logic for particle generation.

Another set of tests involved benchmarking clone-based simulations in EVOLUTION, with variable number of particles and the initial phase distribution *generated by a random number generator*, against the GENESIS simulations using internally generated distribution with shot noise. The underlying physical distribution was assumed to be a constant-current one. (We varied the undulator length to make sure that at the end of the run saturation has not yet been reached.) The parameters of these simulations are listed in Table 1.

Table 1: FEL Parameters for the Benchmarking Runs

Total charge (nQ)	$3.301935 \cdot 10^{-2}$
$\lambda_{FEL}(\mu m)$	0.7
Bunch length (μm)	35
γ_0	266.45
Undulator period (m)	0.05
$L_u(m)$	2.70

In these tests, we used distributions with no initial energy spread, and used the rms uncorrelated (slice) gamma spread for comparison of the instability growth rates in GENESIS and EVOLUTION simulations. We varied the number of particles per slice from $\sim 2k$ to $\sim 32k$.

The agreement is at about 10% level, with $\sigma_\gamma \sim 2.2 \pm 0.2$ in EVOLUTION runs as compared to $\sigma_\gamma \sim 2.4 \pm 0.5$ seen in GENESIS runs. At the visual-inspection level, the degree of agreement can be gauged from Figure 1 that shows the longitudinal phase space of the bunch at the end of the undulator for the case of 32768 particles per slice.

The shot noise in EVOLUTION decreases very slowly with number of particles per slice, showing $\sim 10\%$ increase of the gain length as the number per slice increased by a factor of 16. This indicates that the clone-based approach is sufficiently robust when it comes to correctly modeling the effects of the shot noise.

Because SASE process starts from shot noise in the input distribution, radiation from FEL operating in a high gain

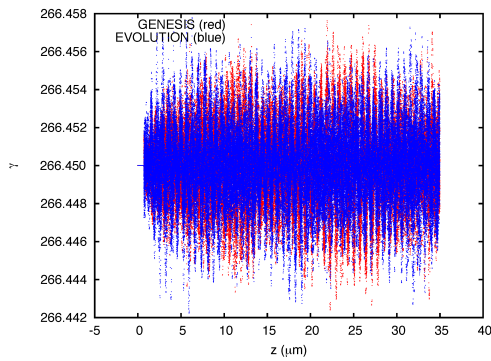


Figure 1: Longitudinal phase space of the bunch at the end of the undulator in 32768-particle-per-slice simulations with GENESIS and EVOLUTION.

linear regime is a random process with well-defined statistical properties [8]. In our initial tests of EVOLUTION, we focus on time and spectral field correlation functions. The first order spectral correlation function is defined in terms of Fourier components $\tilde{E}(\omega)$ of the field as

$$g_1(\omega - \omega') = \frac{\langle \tilde{E}(\omega) \tilde{E}^*(\omega') \rangle}{\left\{ \langle |\tilde{E}(\omega)|^2 \rangle \langle |\tilde{E}(\omega')|^2 \rangle \right\}^{1/2}}. \quad (3)$$

(All averages are over an ensemble of realizations.) For a flat-top current distribution of duration T , this expression becomes

$$g_1(\omega - \omega') = \sin\left(\frac{(\omega - \omega')T}{2}\right) \Big/ \frac{(\omega - \omega')T}{2}. \quad (4)$$

A mathematically equivalent measure of correlation that may be preferable in numerical work is the first order correlation function in the time domain, expressed in terms of the slowly varying complex field amplitude $\tilde{E}(t)$ as

$$g_1(t - t') = \frac{\langle \tilde{E}(t) \tilde{E}^*(t') \rangle}{\left\{ \langle |\tilde{E}(t)|^2 \rangle \langle |\tilde{E}(t')|^2 \rangle \right\}^{1/2}}. \quad (5)$$

In the high gain linear regime this can be expressed as

$$g_1(t - t') = \exp\left(-\frac{9\rho^2\omega_0^2(t - t')^2}{\sqrt{3}\Gamma z}\right), \quad (6)$$

where ω_0 is the resonance frequency, ρ is the efficiency parameter, and Γ the gain parameter. We use the above expressions for benchmarking statistics of a large number of single-run realizations.

We will present results of these tests in a separate publication in the near future.

ACKNOWLEDGEMENTS

This work was supported by the DOE Office of Science, Office of Nuclear Physics, grants No. DE-FG02-08ER85182 and DE-SC0000835, including the use of NERSC under contract No. DE-AC02-05CH11231, and by the Office of Basic Energy Sciences grant No. DE-SC0007576. Partial support was provided by the Tech-X Corporation.

REFERENCES

- [1] V.N. Litvinenko and Y.S. Derbenev, Phys. Rev. Lett. 102, 114801 (2009)
- [2] V.N. Litvinenko, “Macro-particle FEL model with self-consistent spontaneous radiation,” unpublished (2002)
- [3] S. Reiche, “GENESIS 1.3: a fully 3D time-dependent FEL simulation code,” Nucl. Instrum. Methods Phys. Res., Sect. A, **429**, 243 (1999).
- [4] W. Fawley, GINGER FEL Code Manual, <http://www-ssl.slac.stanford.edu/lcls/technotes/lcls-tn-04-3.pdf>
- [5] W.M. Fawley, PRST-AB 5, 070701 (2002).
- [6] G.I. Bell *et al.*, these Proceedings.
- [7] C.A. Brau, “Free-Electron Lasers”, Academic Press, 1990.
- [8] E.L. Saldin *et al.*, “Statistical properties of radiation from VUV and X-ray free electron laser”, Optics Communications **148**, 383-403 (1998).