

GENESIS 1.3 — A Fully 3D Time Dependent FEL Simulation Code

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Abstract

Numerical simulation codes are basic tools for designing Free-Electron-Lasers (FEL). They are used to study the impact of different parameters, e.g. wiggler errors and external focusing, which allow FEL users to optimize the performance. For faster execution some simulation codes assume radial symmetry or decompose the radiation field into a few azimuthal modes, although then this treatment does not include the full description of the FEL. This contribution describes the new FEL code GENESIS 1.3 which uses a fully 3 dimensional representation of the FEL equations in the paraxial approximation for time dependent and steady state simulations of single-pass free electron lasers. In particular this approach is suitable for cases where the radial symmetry is broken by the electron beam distribution as well as by wiggler errors, betatron motion and off axis injection of the electron beam. The results, presented here, are based on the parameters of the TESLA Test Facility FEL at DESY.

1. Introduction

With the design and construction of Free Electron Lasers (FEL), many codes have been developed [1, 2, 3, 4, 5] over the years in order to describe the physics taking place in different regimes. Recent research is done on the field of Self-Amplified Spontaneous Emission (SASE) FEL [6, 7, 8]. To investigate the properties of this radiation source as well as the extension of SASE FEL's wave length to the VUV or X-ray regime, new codes or extensions of established codes are needed. To cover these aspects and others such as the influence of wakefields, a time dependent code has been developed called GENESIS 1.3.

The algorithm to solve the FEL equation in the paraxial approximation is similar to TDA3D [2]. In fact GENESIS 1.3 is mainly based on TDA3D although major modifications have been made. One of the major improvement is the replacement of the radial mesh with a full Cartesian mesh using the Alternating Direction Implicit (ADI) integration scheme [9] to solve the field equation. This allows the user to study non axi-symmetric cases such as undulator field errors or beam halos.

The basic idea of the extended algorithm for

time dependent simulation is to solve the equation for a given slice of the electron bunch and a certain integration length significantly smaller than the gain length before advancing the radiation field to the next slice and replacing it with the radiation field of the trailing slices. This allows only a fractional part of the electron beam and radiation field to be kept in memory.

The source code of GENESIS 1.3 is written in standard ANSI Fortran 77 and can be compiled and linked with common Fortran compilers on any platform. The two restrictions for a successful execution are the support of double complex precision numbers and enough memory for time dependent simulation. During execution the code will read from or write to files using only standard Fortran formats such as sequential or direct access and formatted or unformatted in- and output. GENESIS 1.3 does not support any graphics as output. For visualization of the output data the postprocessor XGENESIS can be used running under the IDL environment [10].

So far the tests which have been made do not show any significant deviation from other well tested codes or analytic results. The CPU time

Electron Beam	
Energy	250/1000 MeV
Energy Spread	0.5/1.0 MeV
Normalized Emittance	2π mm mrad
Ave. Beam Size	60/50 μm
Peak Current	500/2500 A
Bunch Length	250/50 μm
Undulator	
Number of Modules	3/5
Length of Modules	4.5 m
Period Length	2.73 cm
Undulator Peak Field	0.497 T

Table 1. Parameters of TTF-FEL used for the simulations. If two values are given the first one corresponds to Phase I of the TTF-FEL, the second to Phase II.

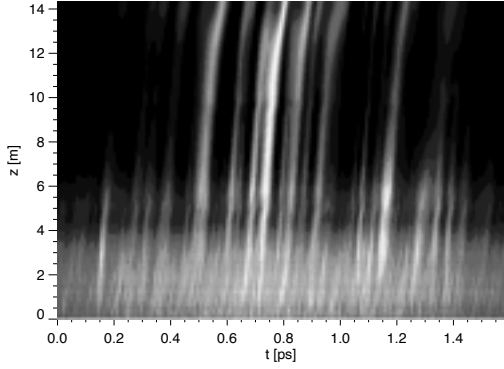


Fig. 1. Radiation power of TTF-FEL (Phase I) versus longitudinal position in the electron bunch (horizontal axis) and undulator (vertical axis). The radiation pulse is normalized to unity for all undulator positions to exclude the dominant exponential growth of the radiation field.

consumption is moderate and steady state simulation, even on Personal Computers, will run in the range of minutes. For time dependent simulation the CPU time scales linearly with the number of macroparticle slices.

To illustrate the application regime of GENESIS 1.3, only few important examples will be shown in this paper. All simulations are based on the parameters of the TESLA Test Facility Free Electron Laser (TTF-FEL) which are listed in Table 1.

2. Time Dependent Simulation

One of the most important applications of time dependent codes is the simulation of SASE FEL's. Following the algorithm described in [11] spontaneous emission seeds the FEL amplifier instead of

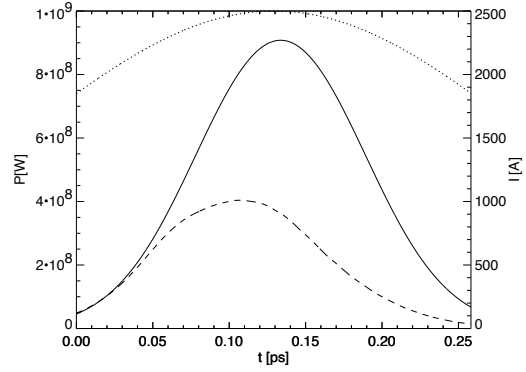


Fig. 2. FEL radiation of TTF-FEL (Phase II) including energy losses of the electron beam due to wakefields (dashed line). The power of the radiation pulse is significantly decreased in comparison to the FEL radiation excluding the effect of wakefields (solid line). Both simulations used the same set of parameters such as the same longitudinal beam current profile (dotted line) and same seeding field.

an external seeding field commonly used in steady state simulations. As an example a compact representation of the result for a single run is shown in Fig. 1 using the parameters of the TTF-FEL Phase I (see Table 1). For each longitudinal position in the undulator (vertical axis) the radiation pulse (horizontal axis) is normalized in such a way that the maximum always has the same value. In this way the structure of the pulse is clearly visible for any position in the undulator. Otherwise the exponential growth of the SASE FEL amplification process will dominate. It is seen that the number of spikes is decreasing along the undulator and the contrast is enhanced. Both effects arise due to growing longitudinal and transverse coherence.

To demonstrate another application regime for time dependent simulation, the influence of wakefields on the performance of the TTF-FEL is investigated. This is of particular concern for Phase II with its short rms bunch length of 50 μm . The geometric and electromagnetic properties of the beam pipe provide three major sources for wakefields: conductivity, surface roughness and geometric changes of the beam pipe along the undulator. For the parameters of the TTF-FEL all three wake potentials have nearly the same amplitude but different shapes [12]. For a time dependent simulation covering a length of about 100 μm around the peak current, the gradient of the total wake potential varies between -100 keV/m and 30 keV/m.

Because most electrons are shifted away from the FEL resonant condition due to the wakefields,

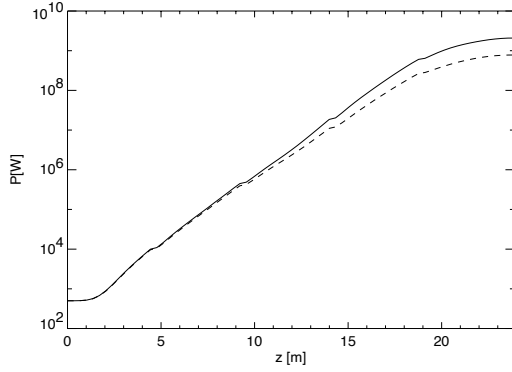


Fig. 3. Radiation power versus undulator position including (dashed line) and excluding (solid line) wakefields.

the total gain is significantly reduced. For a position close to saturation the radiation pulse is plotted in Fig. 2. In contrast to the undisturbed FEL performance the maximum of the radiation pulse is trailing behind the maximum of the beam current distribution. The reason is that slippage of the radiation field has less influence than the detuning of the electron beam which is stronger in the front part of the electron beam.

In Fig. 3 the radiation power with and without wakefields taken into account is plotted as a function of the longitudinal position in the undulator. It is seen that the power reduction due to wakefields is larger in the last part of the undulator due to the accumulated energy losses of the electron beam. The saturation length remains nearly unchanged and is reached in this case when most of the beam is completely detuned.

3. Non Axi-Symmetric Simulation

As an example of broken axi-symmetry the case of undulator field errors for the TTF-FEL (Phase I) is simulated [13].

For a relative rms error of 0.3 % for the field errors the radiation distribution at two positions within the undulator is presented in Fig. 4. At these positions the electron beam centroid was deflected from the undulator axis and bent backwards due to strong focusing. The radiation field, unable to follow the rapid motion of the electron beam, becomes distorted. The steeper edges of the radiation field distribution induce a larger diffraction in addition to a reduced gain guiding because the electron beam position has changed transversely. The lower plot of Fig. 4 shows such a large diffracted part of the radiation field.

The FEL gain is also reduced by other effects

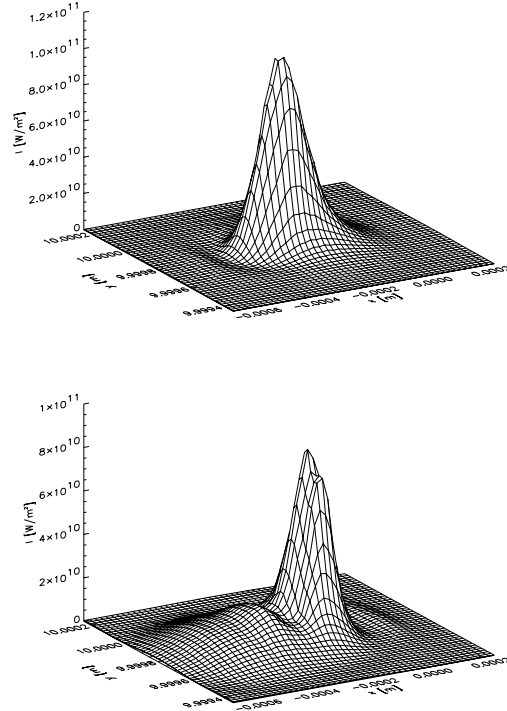


Fig. 4. Intensity of radiation field for FEL simulation including magnetic field errors. The data shows a typical case where the electron beam is kicked towards one direction in the horizontal plane (upper plot) and bent back towards the undulator axis (lower plot).

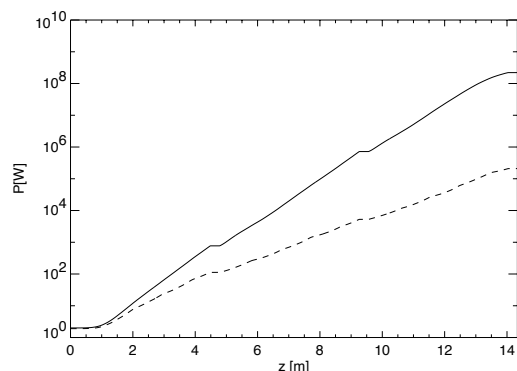


Fig. 5. Radiation power versus undulator position for the TTF FEL (Phase I) including magnetic field errors (dashed line). For the calculation 400 independent runs are averaged with a relative rms field error of 0.3%. The undisturbed FEL performance is shown by the solid line.

such as loss of the synchronization condition of the electron beam and radiation field. For this case the coherent transverse kick reduces the longitudinal velocity of the electron beam. The average power gain versus longitudinal position in the undulator is shown in Fig. 5 with a saturation power reduced by nearly 3 orders of magnitudes relative to the undisturbed motion of the electron beam.

4. Conclusion

Although several FEL codes already exist, there is an increasing demand to cover new aspects of FEL performance in order to keep up with the advance research. GENESIS 1.3 contains several new features and allows the user to describe the problem in a more flexible manner. Even for cases which are not covered by the standard features of GENESIS 1.3, the user has the option to modify the source code for his own purposes, because GENESIS 1.3 is distributed free. Thus GENESIS 1.3 provides a new and useful tool for FEL-physics.

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