CALCULATIONS OF THE SELF-AMPLIFIED SPONTANEOUS EMISSION PERFORMANCE OF A FREE-ELECTRON LASER*

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Abstract

The linear integral equation based computer code (RON: "Roger Oleg Nikolai"), which was recently developed at Argonne National Laboratory, was used to calculate the self-amplified spontaneous emission (SASE) performance of the free-electron laser (FEL) being built at Argonne. Signal growth calculations under different conditions are used for estimating tolerances of actual design parameters. The radiation characteristics are discussed, and calculations using an ideal undulator magnetic field and a real measured magnetic field will be compared and discussed.

1 INTRODUCTION

The code RON was derived from a system of linear integral equations for the particle distribution function in a high-gain FEL [1, 2] and was developed to aid in the actual design of the SASE FEL at Argonne. Specifically it can take into account nonideal magnetic systems such as segmented undulators with distributed focusing and real measured magnetic fields. A series of comparisons with other codes was conducted recently, and the results are presented elsewhere [3].

The system of linear equations describes the evolution of the Fourier harmonics of the electron beam current densities (a set of "thin" beams simulates the emittance of the real beam) versus the longitudinal coordinate *z*, which in the exponential growth regime scale self-similar to the radiated power. To simulate the SASE mode, i.e., the growth of initially uncorrelated density fluctuations, the initial currents for all but one beam were set to zero (similar to the calculation of the Green's function for density fluctuations). It corresponds to the situation when one particle (delta function of the electric current) is added to the beam with a time-independent (constant) current; then the charge density perturbation in the beam caused by the radiation of the particle is calculated. The code also allows for the input of an external electromagnetic wave (the seed signal) in the form of a Gaussian beam.

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2 CALCULATIONS

Initially we used RON to calculate signal growth of the beam current density under different conditions and to determine tolerances for the beam and the undulator segments. More recently we have added explicit calculation of the radiation field (on an arbitrary grid) and the capability to study the effect of real magnetic field errors on the performance. Further, since the code is fast, it has been feasible to run the code in an optimization algorithm to determine the optimal break length between undulator segments. In the following, we present some of our recent results.

2.1 Beam and mechanical tolerances

The code was initially used to investigate a variety of different mechanical designs including finding tolerances of important parameters for the design. First we showed that a high-gain FEL could be built without any significant loss in performance by using a distributed focusing approach with separated quadrupoles in break sections (between planar undulator sections) instead of a combined focusing undulator design. Second, alignment and beam tolerances were determined for the current FEL design with distributed focusing. We found that the undulators need to be aligned to better than 50 μm vertically, but both longitudinally and horizontally the tolerances are much more relaxed (1.0 mm). A summary of the results including beam tolerances is given in [4, 5]. We also made initial investigations of the sensitivity to magnetic field errors and found that a $\Delta K/K \sim 0.01/3.1 \sim 0.3\%$ variation between undulator segments was well within an acceptable range. This value was later confirmed using a measured magnetic field as input - also see section 2.4 below.

2.2 Optimal break length between undulator segments

The calculation of the optimal length of the breaks between undulators has to take into account the real magnetic field at the ends of undulators. It has been possible to run the code in an optimization loop to optimize the break length between undulator segments because of its speed (less than one min on a Pentium II 333 MHz PC per function evaluation). Optimization was carried out by varying two parameters: the detuning parameter (radiation frequency) and the break length. The value of the current density after five undulator sections was chosen as the figure of merit and the optimization was done using the Newton method. A typical optimization run took about one hour.

2.3 Radiation field

In the actual design, equipment is installed in each break section for beam and radiation diagnostics. It is extremely valuable to be able to calculate the radiation that can be measured experimentally, and we have therefore extended the code to calculate the radiation field on an arbitrary grid outside any undulator segment. We calculate the electrical field in the paraxial approximation that is given by the following expression

$$E(\vec{r}) = \frac{ik}{c}\int_0^z \sum_n \frac{j_x^n e^{ik(z-z')} e^{ik\frac{(x-x_n)^2+(y-y_n)^2}{z-z'}}}{z-z'} dz',$$

where c is the speed of light, $k = \omega/c$ is the wave number, j_x^n is the x-component of n-th beam current, and $\vec{r}$ is the screen coordinate. The radiation pattern shown in Fig. 1 was obtained near the fundamental wavelength at 518 nm at 8.0 m from the end of the first undulator segment (when only one undulator segment is installed) using a beam energy of 220 MeV.

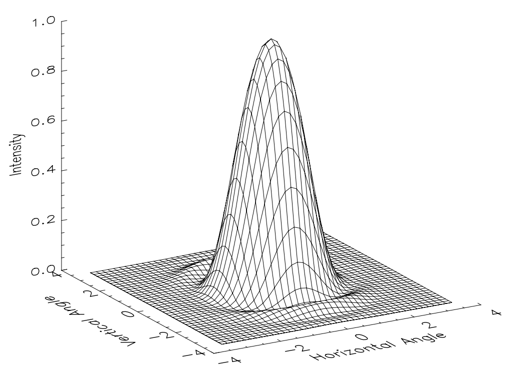

Figure 1: Angular distribution of the radiation field (square of the amplitude of the electric field). The angles are given in units of the inherent radiation opening angle $\sqrt{\lambda/2L}$, where λ is the wavelength and L is the length of one undulator segment.

2.4 Results using a measured magnetic field

Magnetic measurements of the undulators consist of large arrays of field values with typically up to one hundred points per undulator period. The period-averaged code RON needs a transformation of these arrays to smaller arrays with a fewer number of points, which to first order have the same influence on the particle motion. At each integration step in RON, the values of the undulator deflection parameter K and the vertical and the horizontal kick angles are read. (The integration step is typically one or several periods long.) A utility code was written that finds the arrays of undulator deflection parameters (K values) and horizontal kicks from a measured vertical magnetic field. (For the Argonne FEL, there is no horizontal focusing by the undulators.) The array of kicks was calculated to provide the same horizontal displacement at the end of each step as the averaged real field (see polygonal approximation in Fig. 2). The array of K values was derived from the slope of the phase versus distance. An “effective” magnetic length of the undulator was also determined by adjusting the length of the first and the last integration step.

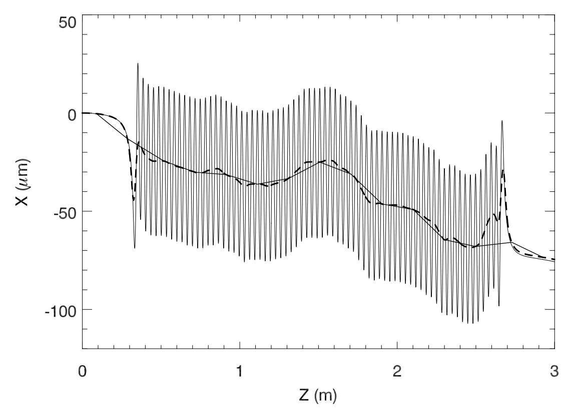

Figure 2: Approximation of the real electron trajectory with a polygonal curve. Real trajectory (thin solid curve), averaged trajectory (dashed curve), and polygonal approximation (thick solid curve) for one undulator segment calculated at 220 MeV.

The typical change in the K value from one step to another was about 0.3% as found from the utility code. For simulation purposes, we replicated the input values for five undulator segments because we had measured data for only one undulator. The calculated bunching of the beam current density is shown in Fig. 3.

Our results indicate that the magnetic field errors of real undulators for the Argonne FEL have little influence on the FEL performance. This is indeed a very important result, and it indicates that the undulators fabricated for this project are of high quality and in many cases may be treated as ideal. The measurement and tuning of the undulators are described elsewhere [6].

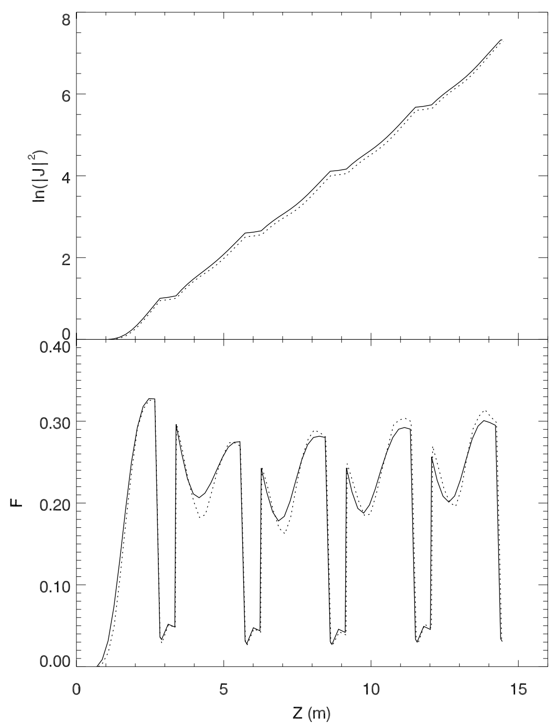

Figure 3: The calculated natural logarithm of the beam current density (top) and the dimensionless scaling factor (bottom) for the FEL using a replicated measured magnetic field from one undulator (dotted curve) versus an ideal field (solid curve).

3 SUMMARY

We have provided a few examples of the flexibility of the code RON, which has been valuable in the actual design of the undulator and break sections of the Argonne FEL. Further developments of the code include a more accurate simulation of undulator displacements and improvements to the initial transverse beam distribution functions (for simulation of the emittance), which is especially important for simulation of shorter wavelength FELs. The option to take into account horizontal field errors is also in progress.

4 REFERENCES

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