MINERVA, A NEW CODE TO MODEL FREE-ELECTRON LASERS

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Abstract

Simulation codes modeling the interaction of electrons with an optical field inside an undulator are an essential tool for understanding and designing free-electron lasers (FELs). As there exists a large variety of FELs ranging from long-wavelength oscillators using partial wave guiding to soft and hard x-ray FELs that are either seeded or starting from noise, a simulation code should be capable of modeling this huge variety of FEL configurations. A new code under development, named MINERVA, will be capable of modeling such a large variety of FELs. The code uses a modal expansion for the optical field, e.g., a Gaussian expansion for free-space propagation, and an expansion in waveguide modes for propagation at long wavelengths, or a combination of the two for partial guiding at THz frequencies. MINERVA uses the full Newton-Lorentz force equation to track the particles through the optical and magnetic fields. To allow propagation of the optical field outside the undulator and interact with optical elements, MINERVA interfaces with the optical propagation code OPC. Here we describe the main features of MINERVA and give various examples of its capabilities.

INTRODUCTION

A variety of different free-electron laser (FEL) simulation codes have been developed over the past several decades such as GINGER [1], MEDUSA [2], TDA3D [3], and GENESIS 1.3 [4] among others. Typically, these codes undergo continuous development over their usable lifetimes. As a result, the codes become increasingly complex as new capabilities are added or older capabilities are deleted, and this tends to hobble their performance. It also renders it increasingly more difficult to make further modifications that might be needed. Because of this, we decided to develop a new code using a "clean-slate" approach having the properties and characteristics that we desired. We designate this new code as MINERVA.

The organization of the paper is as follows. The properties of MINERVA are described in the second section. We describe the comparison of MINERVA with the SPARC SASE FEL [5] in the third section, and a comparison with the long wavelength JLAB IR-upgrade FEL oscillator [6] in the fourth section. A summary and discussion follows.

PROPERTIES OF MINERVA

The formulation of MINERVA describes the particles and fields in three spatial dimensions and includes time dependence as well. Electron trajectories are integrated using the complete Newton-Lorentz force equation. No wiggler-averaged-orbit approximation is made. The magnetostatic fields can be specified by analytical functions for a variety of analytic undulator models (such a planar or helical representations), quadrupoles, and dipoles. These magnetic field elements can be placed in arbitrary sequences to specify a variety of different transport lines. As such, MINERVA can set up field configurations for single or multiple wiggler segments with quadrupoles either placed between the undulators or superimposed upon the undulators to create a FODO lattice. Dipole chicanes can also be placed between the undulators to model various high-gain harmonic generation (HGHG) configurations. The fields can also be imported from a field map if desired.

The electromagnetic field is described by a modal expansion. For free-space propagation, MINERVA uses Gaussian optical modes, while waveguide modes are used when the wavelength is comparable to the dimensions of the drift tube. As a result, MINERVA can treat both long and short wavelength FELs. A combination of the Gaussian and waveguide modes is also possible when there is partial guiding at, for example THz frequencies.

The electromagnetic field representations are also used in integrating the electron trajectories, so that harmonic motions and interactions are included in a self-consistent way. Further, the same integration engine is used within the undulator(s) as in the gaps, quadrupoles, and dipoles, so that the phase of the optical field relative to the electrons is determined self-consistently when propagating the particles and fields in the gaps between the undulators.

Particle loading is done in a deterministic way using Gaussian quadrature that preserves a quiet start for both the fundamental and all harmonics. Shot noise is added following the procedure developed for MEDUSA [7], so that MINERVA is capable of simulating SASE FELs.

MINERVA has also been linked to the Optics Propagation Code (OPC) [8,9] for the simulation of FEL oscillators or propagating an optical field beyond the end of the undulator line to a point of interest.

MINERVA is written in Fortran 95 using dynamic memory allocation and supports parallelization using the Message Passing Interface.

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THE SPARC SASE FEL

The parameters of the SPARC SASE FEL [5] are as follows. The electron beam had an energy of 151.9 MeV, a bunch charge of 450 pC, and a bunch width of 12.67 psec. The peak current was approximately 53 A. The x and y emittances were 2.5 mm-mrad and 2.9 mm-mrad respectively, and the rms energy spread was 0.02%. There were six undulators each of which was 77 periods in length (with one period for the entrance up-taper and another for the exit down-taper) with a period of 2.8 cm and an amplitude of 7.88 kG. The gap between the undulators was 0.4 m in length and the quadrupoles (0.053 m in length with a field gradient of 0.9 kG/cm) forming the FODO lattice were located 0.105 m downstream from the exit of the previous undulator. The resonance occurred at a wavelength of 491.5 nm, but the undulator line was not long enough to reach saturation over the six undulators.

The experimental measurement of the pulse energy versus position was compared with the predictions of four simulation codes: GINGER, MEDUSA, PERSEO [10], and GENESIS 1.3. The resulting comparison is shown in Fig. 1 and shows generally good agreement between the codes and between the codes and the experiment.

It is not our purpose here to provide a detailed description of the experiment; rather, we want to demonstrate that MINERVA is also in good agreement with the other codes and, by extension, with the experiment. This is shown in Fig. 2 where we plot the predictions of MINERVA and MEDUSA for the parameters of the SPARC experiment, and which shows that MINERVA is in similarly good agreement with the measured pulse energies.

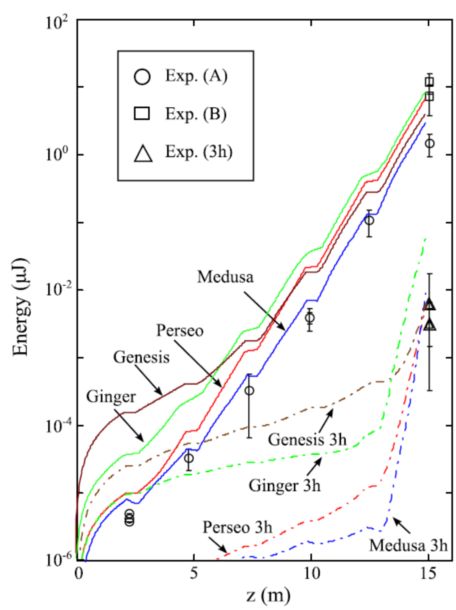

Figure 1: Comparison of GINGER MEDUSA, PERSEO, and GENESIS with the SPARC experiment [5], showing the optical pulse energy as a function of the distance z.

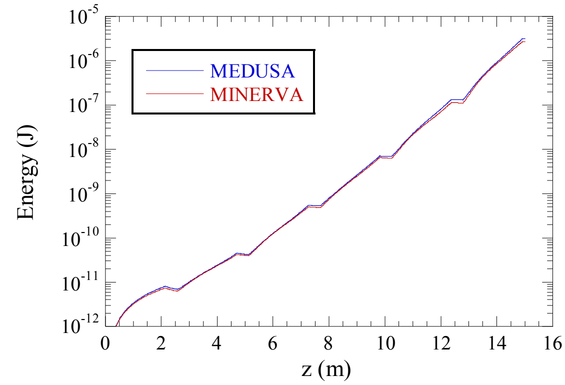

Figure 2: Comparison of MINERVA with MEDUSA for the SPARC experiment, showing the optical pulse energy versus the distance z.

THE JLAB IR-UPGRADE FEL OSCILLATOR

To further investigate the capabilities of MINERVA we also compared the code with an existing long-wavelength FEL oscillator, the IR-upgrade FEL oscillator of the Thomas Jefferson National Accelerator Facility (JLAB) [6]. The JLAB IR-upgrade has already successfully been modeled using MEDUSA [11] and we use the same parameters for MINERVA to model the IR-upgrade. These were a kinetic energy of 115 MeV, an energy spread of 0.3%, a bunch charge of 115 pC, a pulse length of 390 fs, a normalized emittance of 9 mm mrad in the wiggle plane and 7 mm mrad in the plane orthogonal to the wiggle plane, and a repetition rate of 74.85 MHz for the electron beam. The planar undulator was 30 periods long, had a period of 5.5 cm, and a peak on-axis magnetic field of 0.375 T. For a proper electron beam transport through the undulator, we used a one period up- and down taper. The electron beam was focused into the undulator with the focus at the center of the device. The resonator length was about 32 m and the cold-cavity Rayleigh length was 0.75 m. The total loss of the resonator was 21%. For these settings, the wavelength was 1.6 μm.

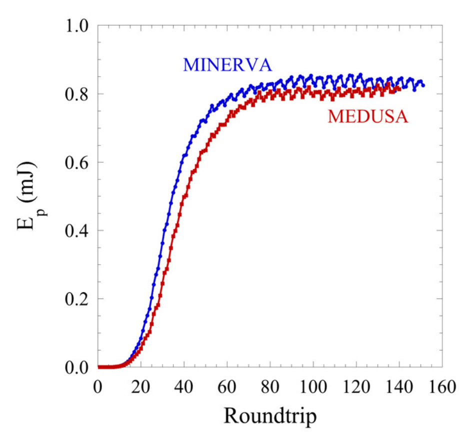

Figure 3: Comparison of MEDUSA and MINERVA for the JLAB IR-upgrade FEL oscillator, showing the intra-cavity pulse energy versus the roundtrip number.

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To simulate the FEL oscillator, OPC takes the optical pulse at the exit of the undulator and propagates the pulse through the resonator to the entrance of the undulator. Both MEDUSA and MINERVA take this optical pulse and propagate it together with a fresh electron bunch through the undulator. This process repeats for a predefined number of roundtrips. The intra-cavity optical pulse energy E_p is shown in Fig. 3 as a function of the roundtrip number for both MEDUSA (red) and MINERVA (blue). Figure 3 shows that, although MINERVA predicts a slightly faster growth, the two codes are in good agreement with each other when the oscillator reaches a stationary state. MINERVA predicts a pulse energy that is 3% higher. Since MEDUSA showed a good agreement with the experiment [11], the same is true for MINERVA.

Each electron bunch contains a kinetic energy of 13.2 mJ. The optical energy extracted from the resonator is 0.16 mJ per pulse. Therefore, the FEL efficiency that follows from the simulation is 1.2%, which is close to the experimental value of 1.4%. The theoretical value is $1/2N_u = 1.7\%$.

The spectrum of the optical pulse extracted from the cavity at roundtrip 150 is shown in Fig. 4 and the center wavelength is, as expected, at 1.6 μm with a -3 dB bandwidth of 24 nm. The transverse spectral intensity is shown in Fig. 5 for the center wavelength and the distribution is close to Gaussian. For wavelengths around the center wavelength the energy distribution is similar to that shown in Fig. 5, however for wavelengths at the edge of the spectrum the transverse distribution changes as is shown in Fig. 6 for two wavelengths that are 60 nm below (Fig. 6a) and 60 nm above (Fig. 6b) the center wavelength and a wavelength of 1.70 μm (Fig. 6c). Although these wavelengths contain hardly any energy, the transverse spectral intensity shows characteristics that change rapidly with the wavelength.

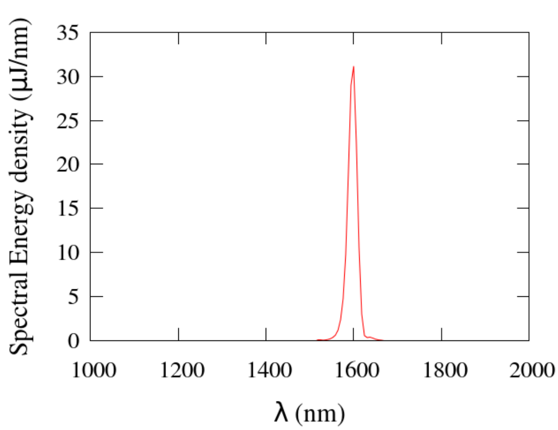

Figure 4: Spectral energy density of the optical output pulse for the IR-upgrade FEL oscillator.

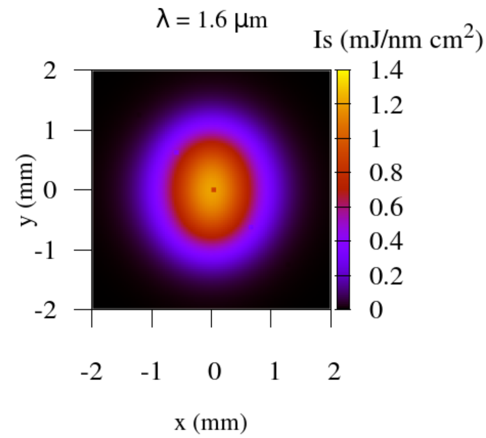

Figure 5: Transverse spectral intensity at the central wavelength of 1.6 μm for the optical pulse after n=900.

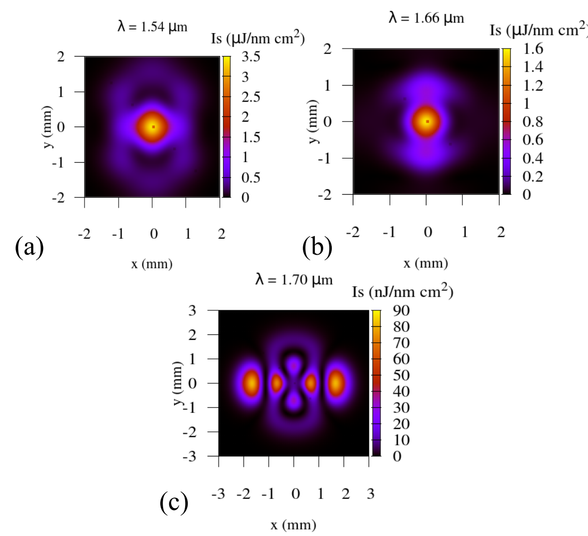

Figure 6: Transverse spectral intensity at wavelengths of 1.54 μm (a), 1.66 μm (b) and 1.70 μm (c) for n=900.

For example, at $\lambda = 1.7$ μm, the emission is predicted to be off-axis with four, about equal, strength maxima located on the x-axis ($y = 0$) and two lower maxima on the y-axis ($x = 0$). The origin of these characteristics is still under investigation, but is likely to consist in the generation of high order modes off the peak wavelength.

SUMMARY AND CONCLUSION

As shown in the paper, the current state of development of MINERVA and MINERVA/OPC yields good agreement for the two experiments studied thus far. Consequently, we feel that MINERVA can accurately, and with confidence, predict the performance of short wavelength FELs. MINERVA is currently in beta-test and development will continue. In particular, the inclusion of waveguide modes will permit the simulation of long wavelength THz FELs.

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