THE APS SASE FEL: MODELING AND CODE COMPARISON[*]

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Abstract

A self-amplified spontaneous emission (SASE) free-electron laser (FEL) is under construction at the Advanced Photon Source (APS). Five FEL simulation codes were used in the design phase: GENESIS, GINGER, MEDUSA, RON, and TDA3D. Initial comparisons between each of these independent formulations show good agreement for the parameters of the APS SASE FEL.

1 INTRODUCTION

The Advanced Photon Source (APS) at Argonne National Laboratory (ANL) is currently commissioning a free-electron laser (FEL) based on the self-amplified spontaneous emission (SASE) process [1]. The design parameters were based on capabilities of the existing APS linear accelerator, the linear theory [2], and simulations. The codes used in the design include GENESIS [3], GINGER [4], MEDUSA [5], RON [6], and TDA3D [7,8]. Comparative simulations were performed using a specific set of input parameters for the APS SASE FEL.

2 CODE DESCRIPTIONS

2.1 GENESIS

GENESIS has its origin in TDA3D, a steady-state simulation code, which has been extended to perform multi-frequency simulations. The radiation field is discretized on a Cartesian grid and solved by the alternating direction implicit (ADI) integration scheme. The transverse motion of the electron beam, described by macroparticles, is calculated analytically, whereas the energy and phase are found by Runge-Kutta integration. In addition to the standard internal generation, an external seeding radiation field, undulator field, and longitudinal variation of the electron beam parameters can be supplied in input files.

2.2 GINGER

GINGER is a 3D multi-frequency particle tracking code with a 2D, axisymmetric representation of the radiation field. The equations of motion are averaged over an undulator period. For non-waveguide simulations, GINGER uses a nonlinear, expanding radial grid, proportional to the square of the radius near the axis, and expands exponentially for large distances from the axis. The outer grid boundary, the number of radial grid zones, as well as the region over which the grid is linear are controlled by input parameters. GINGER is able to simulate a single segment of undulator as well as lumped, quadrupole focusing.

2.3 MEDUSA

MEDUSA is a 3D multi-frequency, simulation code where the electromagnetic field is represented as a superposition of Gauss-Hermite modes and where a source-dependent expansion is used to determine the evolution of the optical mode radius. The field equations are integrated simultaneously with the 3D Lorentz force equations. As such, MEDUSA differs from the other nonlinear simulation codes in that no undulator-period average is imposed on the electron dynamics. It is capable of treating quadrupole and corrector fields, magnet errors, and multiple segment undulators.

2.4 RON

RON is a linear, single-frequency code intended for design optimization of high-gain, short wavelength FELs, with features for multiple-segment undulators, field errors, and distributed focusing elements. The electron motion is along pre-calculated, period-averaged trajectories and the radiation field and the bunched beam current density are calculated at these trajectories from a set of linear integral equations. Explicit calculation of the radiation field (on an arbitrary grid) and the capability to use a measured magnetic field profile as input has been added recently. Although the linearity does not provide the saturated state, it does allow for fast run times.

2.5 TDA3D

TDA3D has been publicly available for over a decade. The latest official release is still a paraxial, single-frequency code. Extensions include non-axisymmetric radiation modes, wiggler errors, a strong quadrupole FODO lattice with arbitrary misalignments, as well as multi-segment undulators. In "expert" mode, arbitrary quadrupole focusing can be simulated.

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0-7803-5573-3/99/$10.00@1999 IEEE.

3 APS SASE FEL DESCRIPTION

The APS SASE FEL uses either a thermionic rf or photocathode rf gun, the 650-MeV 2856-MHz APS linac, two new transfer lines, and a new undulator hall and diagnostic end station. The project will evolve over three phases, to reach saturation in the visible, UV, and VUV wavelength regimes, respectively.

The design is based on known gun performance, constraints imposed by the APS linac, and the characteristics of currently available undulators. Tuning of the undulators has been optimized to meet the performance tolerances of the FEL.

For the simulation, a set of parameters for the first phase was used and a Gaussian electron beam distribution was assumed (Table 1). Test runs were made to determine the minimum number of particles needed in each code to achieve convergence. The optimum wavelength, corresponding to the minimum gain length, was then obtained for each code by scanning in wavelength about the resonant condition (516.75 nm). The optimal wavelengths for the five codes are given in Table 2; however, the fitted gain length is dependent on the fit region. This impacts the exact determination of the minimum and subsequently the peak power at saturation.

Table 1: Simulation and undulator cell parameters

Parameter	Value
γ	430.529
Normalized emittance	5 π mm mrad
Peak current	150 A
Undulator period	3.3 cm
Undulator strength (K)	3.1
Energy spread	0.1%
Input start-up power	1.0 W
Undulator Length	2.4 m
Focusing/diagnostics Gap	36 cm
Quadrupole strength	20 m^{-2}
Quadrupole length	5 cm

Table 2: Optimum wavelengths

Code	Optimum λ (nm)
GENESIS	517.78
GINGER	516.80
MEDUSA	518.82
RON	518.8
TDA3D	517.78

4 RESULTS

In the first comparison, a single-segment parabolic pole face undulator was used. The actual design uses multiple 2.763-m undulator "cells," each of which is composed of a 2.4-m magnetic segment and a 0.363-m section for diagnostics, a combined quadrupole/corrector magnet, and drift space. The second comparison simulates this actual case (less corrector fields) with flat pole face undulators and quadrupoles (Table 1). Note that GINGER was omitted from this second comparison because it does not easily treat the segmented undulator case. The output power versus distance along the undulator for the single segment case is shown in Figure 1. The curves for GINGER and MEDUSA are almost identical and differ primarily in that GINGER predicts a somewhat lower saturated power. The calculated radiated power for RON is scaled from the bunched beam current density that is valid for the behavior in the exponential growth regime only where the radiated power is self-similar to the beam current. Thus, only the gain length in RON should be compared with the other codes. The gain length is almost identical in GINGER, MEDUSA and RON. TDA3D and GENESIS yield nearly identical results, but the gain lengths are slightly longer than found by the other codes.

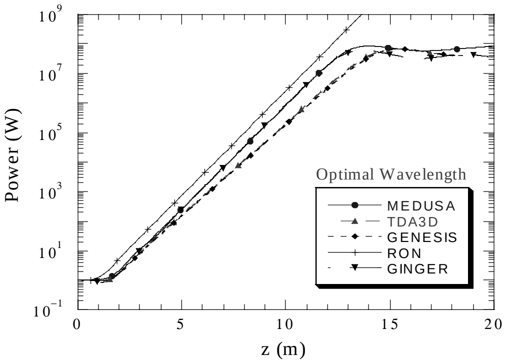

Figure 1: Single segment case

The output power versus distance for the multi-segment case is shown in Figure 2. Here, the shortest gain length is predicted by RON, the longest by MEDUSA, and GENESIS and TDA3D predict gain lengths in between these other results.

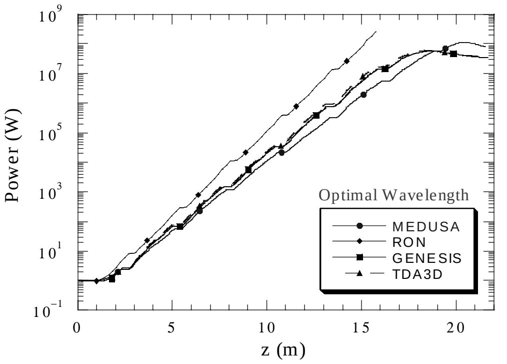

Figure 2: Multiple segment case

Table 3 summarizes the saturation point and power for the single- and multiple-segment cases as determined by the four nonlinear codes at the listed optimal wavelengths.

Table 3: Saturation point and power

Code	z(m)	Case 1 (MW)	Case 2 (MW)
GENESIS	15.5	69.4	58.0
GINGER	13.7	61.7	N/A
MEDUSA	14.0	87.4	109.4
TDA3D	15.4	68.9	61.3

Comparisons of the gain length predicted by the codes and by the linear theory for the single segment case were also performed. The energy spread was varied between 0.0-0.2%, the peak current between 50-300 A, and the normalized emittance between 1-10 π mm-mrad. Figures 3, 4, and 5 show the gain length versus these variations, respectively. It is evident from the figures that the codes are essentially in reasonable agreement over the entire range of parameters studied. In general, it appears that GENESIS and TDA3D predict slightly longer gain lengths than the linear theory, while GINGER, MEDUSA, and RON predict slightly shorter gain lengths. Note that the linear theory is used for comparison purposes only, and should not be assumed as "perfect" but considered as an additional model. While the maximum discrepancies are of the order of 20% at some of the extremes of these parameter ranges, the maximum discrepancies are typically less than 15% for the parameters of interest in the APS SASE FEL.

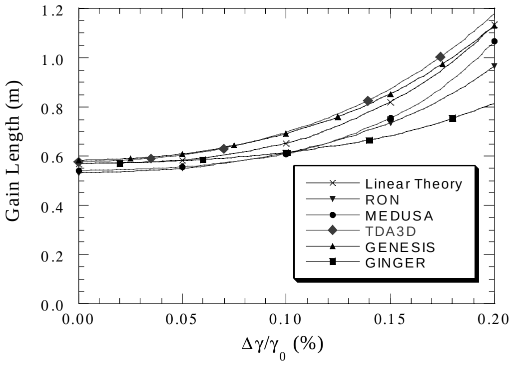

Figure 3: Gain length versus energy spread

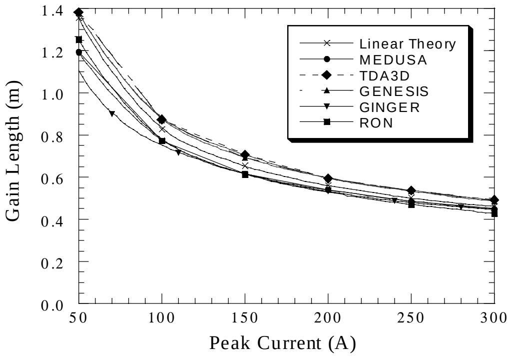

Figure 4: Gain length versus peak current

5 CONCLUSIONS

In summary, GENESIS, GINGER, MEDUSA, RON, and TDA3D all show reasonable agreement with each other and with the linear theory for the first-phase APS SASE FEL parameters, giving greater confidence to the required length of undulator needed to reach full saturation.

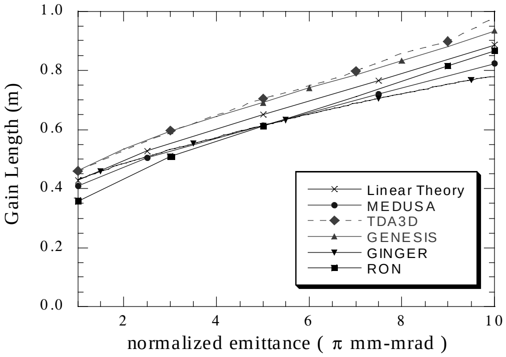

Figure 5: Gain length versus normalized emittance

6 REFERENCES

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