COMPARATIVE DESIGN STUDIES FOR THE BESSY FEL PROGRAM USING THE MEDUSA AND GENESIS SIMULATION CODES

H.P. Freund#, Science Applications International Corp., McLean, VA 22102, USA
S.G. Biedron, Argonne National Laboratory, Argonne, IL 60439, USA
D. Krämer, A.Meseck, B. Kuske, M. Abo-Bakr, K. Goldammer, BESSY, Albert-Einstein-Strasse 15, 12489 Berlin, Germany

Abstract

The BESSY FEL is based on a seeded cascade of High Gain Harmonic Generation (HGHG) sections followed by an amplifier to produce fully transverse and longitudinally coherent and stable short wavelength output. Here, we report on comparative design studies carried out using the MEDUSA, and GENESIS simulation codes. These codes are based on different assumptions: hence, the comparative study for an HGHG cascade is important. We report the results where the parameters of each stage have been optimized.

INTRODUCTION

We report on comparative design studies for the BESSY Technical Design Report (TDR) carried out using the MEDUSA [1], and GENESIS [2] simulation codes. These two codes have each been used to successfully predict a variety of FEL designs and have agreed well with a number of important experiments. In addition, they were included in a comparative study of FEL simulation that reported substantial agreement between the codes for the specific configurations studied [3]. However, these codes are based on different assumptions. GENESIS treats the particle dynamics using a wiggler-averaged orbit approximation, the transverse electromagnetic field is treated using a field solver, and harmonics are not included. MEDUSA does not use the wiggler-averaged orbit approximation to treat particle dynamics, the transverse fields are treated using a Gaussian modal superposition, and harmonics are included self-consistently. Hence, the comparative study is important.

Table 1: Summary of the wiggler parameters from the BESSY Technical Design Report.

	MODULATOR			RADIATOR		
Stage	λ_w (cm)	B_w (kG)	λ_{seed} (nm)	λ_w (cm)	B_w (kG)	λ_{rad} (nm)
1	12.2	11.89	279.5	9.2	7.994	55.9
2	9.2	7.994	55.9	7.0	5.056	11.18
3	7.0	5.056	11.18	5.0	4.300	3.73
4	5.0	4.300	3.73	2.85	4.358	1.24
Amp			1.24	2.85	4.358	1.24

The BESSY Technical Design Report describes several possible high-gain-harmonic generation (HGHG) configurations, and we settled on one of these for the comparison. Specifically, on the high-energy configuration which consists of a cascade through four HGHG stages followed by a high-gain amplifier. The basic parameters for the modulators and radiators for these stages are shown in Table 1.

THE HGHG CASCADE

The first priority in modeling the system is to optimize the beam energy. The GENESIS simulations used a beam energy of 2299.4 MeV. A scan in energy using MEDUSA showed an optimal energy of 2307.0 MeV. This represents a difference between the two codes of about 0.3% and is not considered to be significant. In addition to the energy, we used a peak current of 1750 A, a normalized emittance of 1.5 mm-mrad, and an energy spread of 0.01%. In the MEDUSA simulations, we assumed an initial seed laser pulse for the first stage with a power of 500 MW. The dispersive sections in all stages were identical and contained chicanes consisting of four dipoles, each with a length of 0.25 m and a separation of 0.13 m. The separation between the modulator and the first dipole and the last dipole and the radiator were also 0.13 m, yielding a total separation length between the modulators and radiators of 1.65 m. Since MEDUSA propagates the beam and radiation self-consistently both in the wigglers and the dispersive sections, we had to optimize the bunching in the chicanes by varying the dipole field strengths. Further, the separations between the different stages varied as follows: 1.745 m (Stage 1 → 2), 2.030 m (Stage 2 → 3), 1.650 m (Stage 3 → 4), and 1.5675 m (Stage 4 → Amplifier). The output light from the radiator of each stage is used as the seed for the modulator in the succeeding stage, and the light is propagated from the end of the radiator to the start of the next modulator. Since there is no interaction with the electron beam in this region, the light is not guided and expands freely.

Table 2: Summary of the wiggler parameters found using the MEDUSA code.

	MODULATOR			RADIATOR		
Stage	λ_w (cm)	B_w (kG)	λ_{seed} (nm)	λ_w (cm)	B_w (kG)	λ_{rad} (nm)
1	12.2	11.89	279.5	9.2	7.994	55.90
2	9.2	7.994	55.9	7.0	5.056	11.18
3	7.0	5.056	11.18	5.0	4.318	3.73
4	5.0	4.318	3.73	2.85	4.689	1.24
Amp			1.24	2.85	4.678	1.24

#henry.p.freund@saic.com

It is known that there are differences in the "tuning" between the various FEL simulation codes, so part of the effort was to retune some of the run parameters; in particular, the beam energy (mentioned above) and wiggler field strengths. This also involves identifying the optimal dipole fields in the chicanes. Note that this process is complex and involves optimizing these parameters for each stage before proceeding on to the succeeding stage. A summary of the optimal modulator and radiator parameters found using MEDUSA is shown in Table 2. We held the wiggler periods fixed, and note that the parameters for the first two stages are identical, but that the amplitudes for the Stage 3 radiator, Stage 4 modulator and radiator, and amplifier wiggler are retuned slightly.

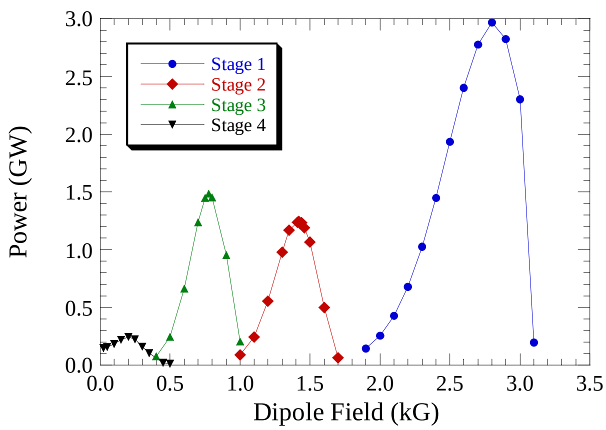

Figure 1: Output power from the radiators in each stage versus dipole field strengths in the chicanes as predicted by MEDUSA.

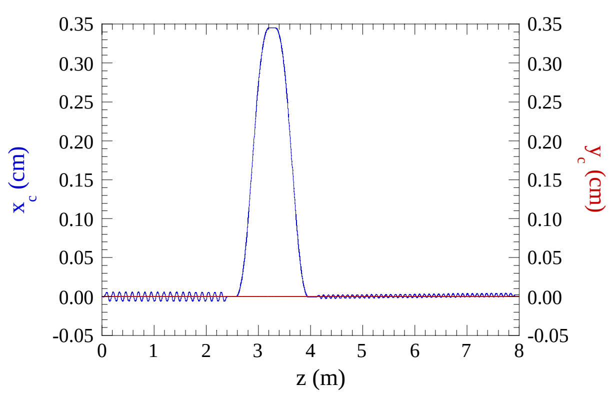

Figure 2: Beam propagation through the 1st stage as seen using MEDUSA.

The effect of variations in the dipole fields in the chicanes is shown in Fig. 1 where we plot the output power from the radiator in each stage versus dipole field strength. Observe that the optimal dipole field strength tended to decrease for each successive stage, which were found to be: 2.80 kG (Stage 1), 1.42 kG (Stage 2), 0.78 kG (Stage 3), and 0.20 kG (Stage 4). Observe that the output from stages 1 – 3 vanishes in the limit where the dipole field in the chicane vanishes, and that this means that the interactions in the radiators in these stages disappears without the enhanced bunching in the chicanes. However, this is not the case in stage 4 where substantial power is found even in the absence of the chicane. We attribute this to the difficulty in bunching at the shortest wavelength, which magnifies the relative effect of nonlinear harmonic generation. Hence, it may be possible to dispense with the chicane altogether in stage 4.

Some discussion is in order regarding beam propagation in MEDUSA through each HGHG section and what the optimal dipole fields mean in terms of the phase space at the end of the chicane. This propagation is shown in Fig. 2 where we plot the beam centroids in x (x_c in blue on the left axis) and y (y_c in red on the right axis). The x-direction marks the wiggle-plane, and the wiggler motion in the modulator and radiator are clearly shown, as is the displacement of the beam in the chicane. There should be no displacement of the beam centroid in the y-direction, and it is also clear that there is none in simulation. The phase space after the chicane should indicate the enhanced bunching, and this is shown in Fig. 3 for the first stage. The rotation of the phase space showing a "vertical" section of the phase space typically indicates the optimal bunching, and this corresponds to the phase space after the chicanes in each stage.

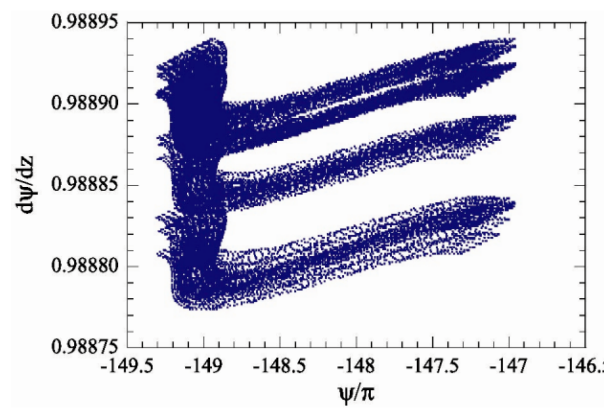

Figure 3: Phase space after the first chicane.

Table 3: Comparison of predicted powers between GENESIS and MEDUSA.

STAGE	GENESIS	MEDUSA
1	4.5 GW	3.34 GW
2	1.8 GW	1.24 GW
3	1.9 GW	1.48 GW
4	0.1 GW	0.25 GW
Amplifier	1.5 GW	4.26 GW

Given these optimized parameters in MEDUSA, we found that, the overall comparisons between the MEDUSA and GENESIS simulations were good. The powers shown in the TDR and those found using MEDUSA are summarized in Table 3. Note that the optimizations performed with MEDUSA were made assuming no bulk loss in beam energy or increase in energy spread or emittance; however, were these effects to be included, then the principal effects would be to retune the wiggler and chicane parameters and to decrease the predicted powers somewhat. We do not expect that any realistic increases in emittance or energy spread would be a serious problem for the design. Also note that the output power from the final amplifier was found after retuning the wiggler amplitude. If we use the same wiggler amplitude as in the radiator in Stage 4 (as was the case for the GENESIS simulations), then we obtain an output power of 1.3 GW, which is close to the result found using GENESIS.

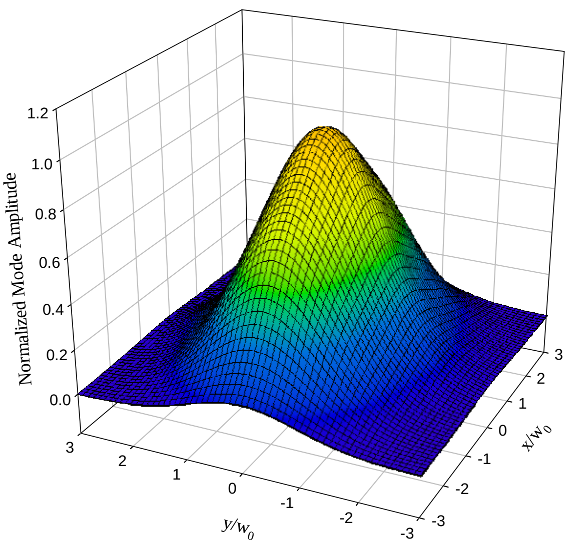

Figure 4: The transverse mode pattern of the 1.24 nm light at the exit from the final amplifier generated using MEDUSA.

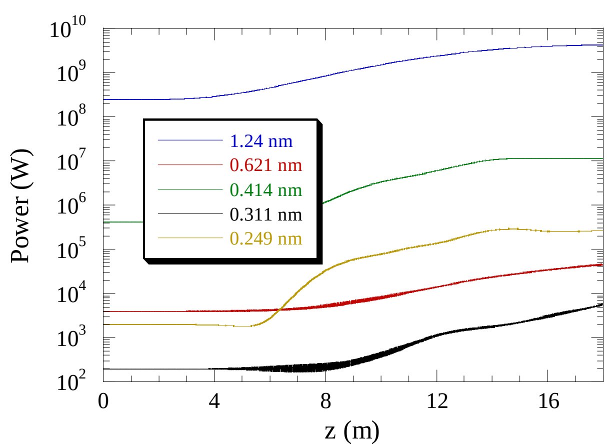

Figure 5: Growth in the fundamental (1.24 nm) wavelength and the 2nd – 5th harmonics in the final amplifier generated using MEDUSA.

Finally, the transverse mode purity at the exit from the final amplifier is shown in Fig. 4, and we see that the higher order mode content is low.

HARMONIC GENERATION

We now turn to the question of the harmonic radiation to be expected from the final amplifier. To this end, the output light at all the harmonics from the 4th Radiator is then propagated to the start of the Final Amplifier section and used as a seed for the amplifier. As such, the harmonic radiation from the final amplifier is a combination of the seeded harmonic power and nonlinear harmonic generation due to bunching at the fundamental wavelength in the final amplifier.

Table 4: The fundamental and harmonic powers in the 4th Radiator and the final amplifier generated by MEUSA.

Wavelength	4th Radiator	Final Amplifier
1.24 nm	0.246 GW	4.26 GW
6.21 Å	4.02 kW	44.8 kW
4.14 Å	413 kW	11.3 MW
3.11 Å	199 W	5.60 kW
2.49 Å	2.04 kW	269 kW

A plot of the MEDUSA results showing the growth of the fundamental and harmonic radiation in the final amplifier is given in Fig. 5, and a summary of the output powers of the fundamental and the harmonics is given in Table 4. The fundamental (1.24 nm) reaches 4.26 GW as before (without the harmonics present in the simulation). As expected, the odd harmonics reach significant power levels, and we find that the 3rd and 5th harmonics reach output powers of 11.3 MW and 269 kW respectively. The even harmonics are at much lower powers and the 2nd (4th) harmonic reaches 44.8 kW (5.60 kW).

SUMMARY

In view of the agreement found between MEDUSA and GENESIS, as well as the overall level of agreement found between these simulation codes and experiments over many years of comparisons, we feel that as long as the electron gun, injector, and linac is capable of reliably delivering pulses with the stated parameters, then the basic performance goals stated in the TDR are eminently practical. Further, the differences between the two codes are complementary and provide additional insights into optimization of the design.

REFERENCES

[1] H.P. Freund *et al.*, IEEE JQE **36**, (2000) 275.
[2] S. Reiche, NIMA **429**, (1999) 243.
[3] S.G. Biedron *et al.*, NIMA **445**, (2000) 110.