ANL/ASD/CP-98996

PARAMETER ANALYSIS FOR A HIGH-GAIN HARMONIC GENERATION FEL USING A RECENTLY DEVELOPED 3D POLYCHROMATIC CODE*

S.G. Biedron†

Advanced Photon Source, Argonne National Laboratory, Argonne, Illinois 60439

H.P Freund

Science Applications International Corporation, McLean, Virginia 22102

L.-H. Yu

Brookhaven National Laboratory, Upton, New York 11973

ABSTRACT

One possible design for a fourth-generation light source is the high-gain harmonic generation (HGHG) free-electron laser (FEL). Here, a coherent seed with a wavelength at a subharmonic of the desired output radiation interacts with the electron beam in an energy-modulating section. This energy modulation is then converted into spatial bunching while traversing a dispersive section (a three-dipole chicane). The final step is passage through a radiative section, an undulator tuned to the desired higher harmonic output wavelength. The coherent seed serves to remove noise and can be at a much lower subharmonic of the output radiation, thus eliminating the concerns found in self-amplified spontaneous emission (SASE) and seeded FELs, respectively. Recently, a 3D code that includes multiple frequencies, multiple undulators (both in quantity and/or type), quadrupole magnets, and dipole magnets was developed to easily simulate HGHG. Here, a brief review of the HGHG theory, the code development, the Accelerator Test

DISCLAIMER

Facility's (ATF) HGHG FEL experimental parameters, and the parameter analysis from simulations of this specific experiment will be discussed.

*Work supported by United States Department of Energy, Office of Basic Energy Sciences, under Contract No. W-31-109-ENG-38.

†biedron@aps.anl.gov

I. Introduction

With the interest in creating a single-pass FEL in the x-ray wavelengths, a few configurations to achieve this have been discussed. One method is high-gain harmonic generation (HGHG) [1,2]. Here, a brief overview of the HGHG theory, the evolution of a code to easily simulate HGHG, a set of parameters for the Brookhaven National Laboratory/Accelerator Test Facility/Advanced Photon Source (BNL/ATF/APS) high-gain harmonic generation (HGHG) [3] experiment, and the results of simulations with this new code are discussed.

II. HGHG Theory

A possible mode of FEL operation capable of providing a very desirable output light beam is HGHG. Here, a coherent radiation source, at a subharmonic of the desired output radiation wavelength, enters a first undulator (the modulative section), which is tuned to the resonance of the electron beam with this subharmonic, for energy modulation. Next, a dispersive section (a three-dipole chicane) is traversed, where spatial bunching is induced imposing a strong higher harmonic content on the electron beam distribution. The beam then enters a second undulator, the radiative section, tuned in resonance to the desired harmonic output wavelength. Coherent radiation and ultimately saturation at this higher harmonic is then achieved within a reasonable number of undulator periods and with an excellent beam quality, as compared to the SASE process. This better beam quality is defined by the coherent seed source, and yet the seed can be at a much lower subharmonic of the radiation. This method could quite possibly be extended to higher energies, where the radiator is tuned to a much higher harmonic, to achieve saturation in the UV, VUV, or x-ray regime. A schematic of the HGHG process is provided in Figure 1.

III. The Multiple-Purpose Simulation Code: MEDUSA

Previously, HGHG simulations were performed in a three-step process [1]. First, the electron beam and seed laser were propagated through the modulative section in a monochromatic FEL simulation code. Second, the electron beam distribution at the exit of the modulative section was mapped into a particle code that tracks the particles through three horizontal dipole magnets. Third, this output was then mapped back into the FEL simulation with only one variation imposed in the code—that the integration over the phase bucket is opened to $n\pi$ instead of π, since the interest is shifted to the n^{th} harmonic. The simulations were performed in this way, since there was no code that could model the dispersive section, the quadrupoles, and simultaneous multiple harmonics.

MEDUSA [4] is a 3D simulation code that represents the electromagnetic field as a superposition of Gauss-Hermite modes, and 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 other nonlinear simulation codes in that no undulator-period average is imposed on the electron dynamics. To simulate HGHG more easily, MEDUSA was extended to simulate the following: 1) multiple-segmented undulators both in quantity and/or type, 2) dipoles to serve in dispersive sections and/or as corrector magnets, 3) quadrupoles for proper matching, and 4) simultaneous multiple frequencies in the form of harmonics and/or closely related sidebands.

IV. The BNL/ATF/APS HGHG Experimental Parameters

There are two distinct project phases of the BNL/ATF/APS HGHG experiment: SASE and HGHG at 5.3 μm. The existing ATF photocathode rf gun, linac, and coherent seed radiation source, a CO_2 laser, define the electron and seed beam parameter base found in Tables 1 and 2, respectively [5]. The magnetic component parameters are found in Table 3.

V. Simulations

For the simulations, we constrain the radiation wavelengths of the seed and output radiation to exactly 10.6 and 5.3 μm, respectively, and assume that the electron beam parameters, strength of the magnetic components, and seed laser power may be adjusted. Also, we have chosen a Gaussian electron beam distribution. First, using the radiative section in a purely monochromatic configuration at 5.3 μm, scans in energy were performed to find the maximum saturated power about the well-known 1D resonance condition. This is illustrated in Figure 2. This electron beam energy was then used to find the best magnetic field in the modulative section for maximum saturated power in the shortest distance, when it was run in a purely monochromatic mode at 10.6 μm, as seen in Figure 3. The electron beam energy and magnetic field of the modulative section were therefore chosen as 40.672 MeV and 1.60 kG, respectively. No energy spread was imposed in these cases. Both of these cases are illustrated in Figure 2.

Next, simulations were performed with the actual HGHG arrangement, in which the seed laser, modulative section, two quadrupoles, the dispersive section, and the radiative section were included. Note that in these simulations, the radiative section begins at 2.65 m. Two types of scans were then performed about the optimum design parameters: varying the dispersion section strength between 1.85 to 2.15 kG and the seed laser power from 0.1 MW to 1.6 MW.

In Figure 3 (a) and (b), the results of the output power (W) and radiation waist versus z (m), respectively, are shown. The power drops off quickly as the dispersive section strength moves away from optimum. This is made apparent in the related reduction in guiding in (b). In Figure 4 (a) - (e), the phase-space (p_z/mc versus ψ) plots are shown at the exit of the dispersive section for five cases of varying the dispersive section strength: 1.85, 1.90, 2.00, 2.05, and 2.15 kG, respectively.

Next, seed laser power scans from 0.1 MW to 1.6 MW at three separate dispersive section strengths (1.85, 2.00, and 2.05 kG) were performed. In Figure 5 (a) and (b), the output power (W) and radiation waist versus z (m), respectively, for the six laser power scans are shown. As with the dispersive section strength scans, both the power and guiding drop off readily as the seed laser power moves away from optimum. In Figure 6 (a) – (f), the phase-space plots are shown at the exit of the dispersive section. Clearly the energy modulation imposed on the beam changes rapidly with slight variations with the input radiation. Although not shown here, the 1.85 and 2.05 kG cases exhibit similar results.

VI. Conclusions and Future Plans

A 3D code, MEDUSA, was developed to treat segmented undulators, dipole magnets, and quadrupole magnets, as well as the interaction of the beam with multiple frequencies. MEDUSA has been used to simulate the HGHG experiment at the Accelerator Test Facilty at Brookhaven National Laboratory, where the multiple frequencies were the input seed laser at 10.6 μm and the output radiation at 5.3 μm. The output power is very sensitive to the choice of seed laser power and the magnetic field strength in the dispersive section. Previously, using the three-step simulation method with TDA3D [6] and a particle tracking code, the HGHG simulations predict a saturated power at 5.3 μm of 37 MW after 1.8 m. The theory also predicts similar results (~35 MW at ~1.8 m). We found a maximum of ~29 MW after ~2 m and plan to further optimize this performance. Future plans also include examining the nonlinear harmonic growth in the radiative section since the entering modulated beam is rich in harmonic content.

VII. References

[1] L.-H. Yu, Phys. Rev A **44**, 5178 (1991).

[2] I. Ben-Zvi et al., Nucl. Instrum. Meth. **A318**, 208 (1992).

[3] L.-H. Yu et al., "The Status of a High-Gain Harmonic Generation Free-Electron Laser Experiment at the Accelerator Test Facility," Proceedings of the 1999 Particle Accelerator Conference, New York, NY, March 29-April 2, 1999 (to be published); L.-H.

Yu et al., "First Lasing of a High-Gain Harmonic Generation Experiment at the Accelerator Test Facility," these proceedings.

[4] H.P. Freund, Phys. Rev. E **52**, 5401 (1995); S.G. Biedron, H.P. Freund, and S.V. Milton, "3D FEL code for the simulation of a high-gain harmonic generation experiment," in *Free-Electron Laser Challenges II*, Harold E. Bennett, David H. Dowell, Editors, Proceedings of SPIE Vol. 3614, 96-108 (1999).

[5] L.-H. Yu, Phy. Rev. E **58**, 4991 (1998).

[6] T.M. Tran and J.S. Wurtele, Computer Physics Communications **54**, 263-272 (1989); S. Reiche and B. Faatz, in NIM Proceedings of the 20th International FEL Conference (FEL98), Williamsburg, VA, USA, 1998, to be published.

LIST OF FIGURES

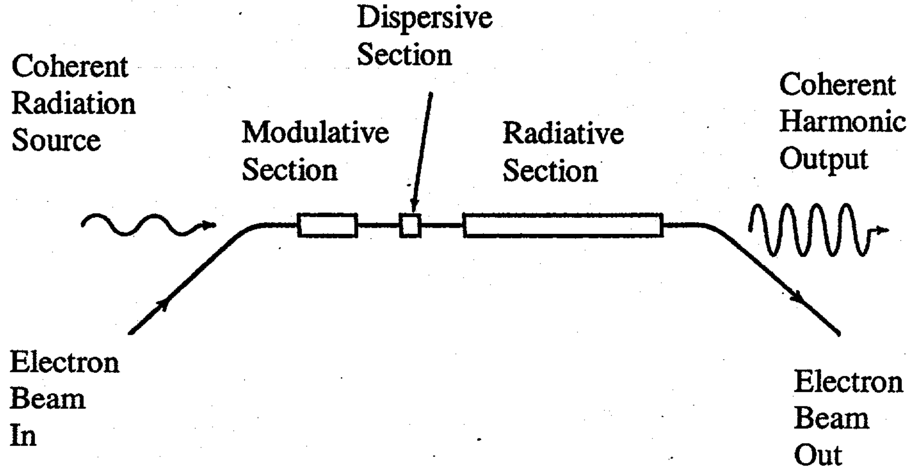
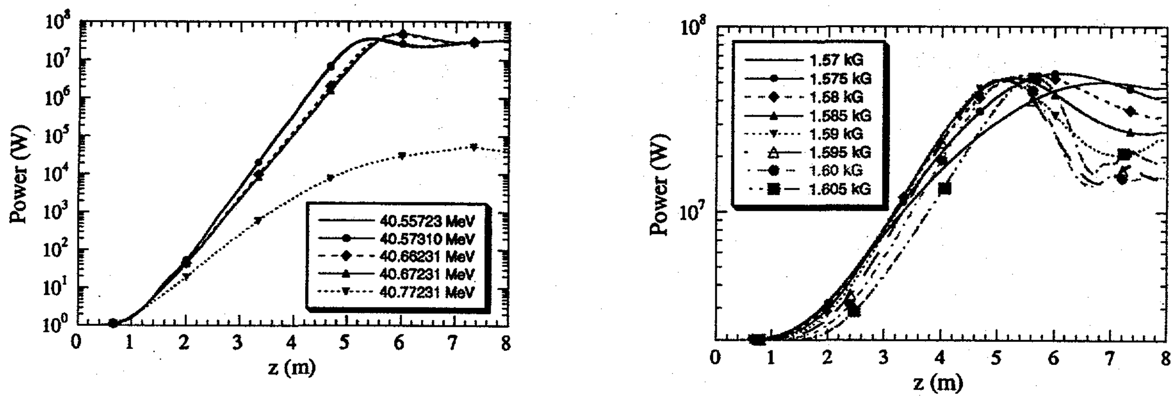
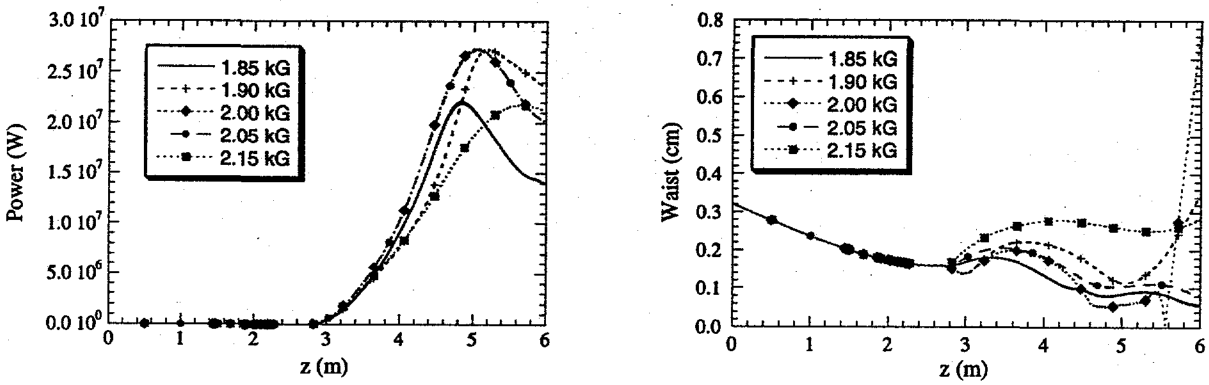

Dispersive Section
Coherent Radiation Source
Modulative Section
Radiative Section
Coherent Harmonic Output
Electron Beam In
Electron Beam Out

Figure 1.



Power (W)
z (m)
40.55723 MeV
40.57310 MeV
40.66231 MeV
40.67231 MeV
40.77231 MeV
1.57 kG
1.575 kG
1.58 kG
1.585 kG
1.59 kG
1.595 kG
1.60 kG
1.605 kG

Figure 2. **(a)** **(b)**



3.0 10^7
2.5 10^7
2.0 10^7
1.5 10^7
1.0 10^7
5.0 10^6
0.0 10^0
Power (W)
0
1
2
3
4
5
6
z (m)
1.85 kG
1.90 kG
2.00 kG
2.05 kG
2.15 kG
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Waist (cm)
z (m)

Figure 3. **(a)** **(b)**

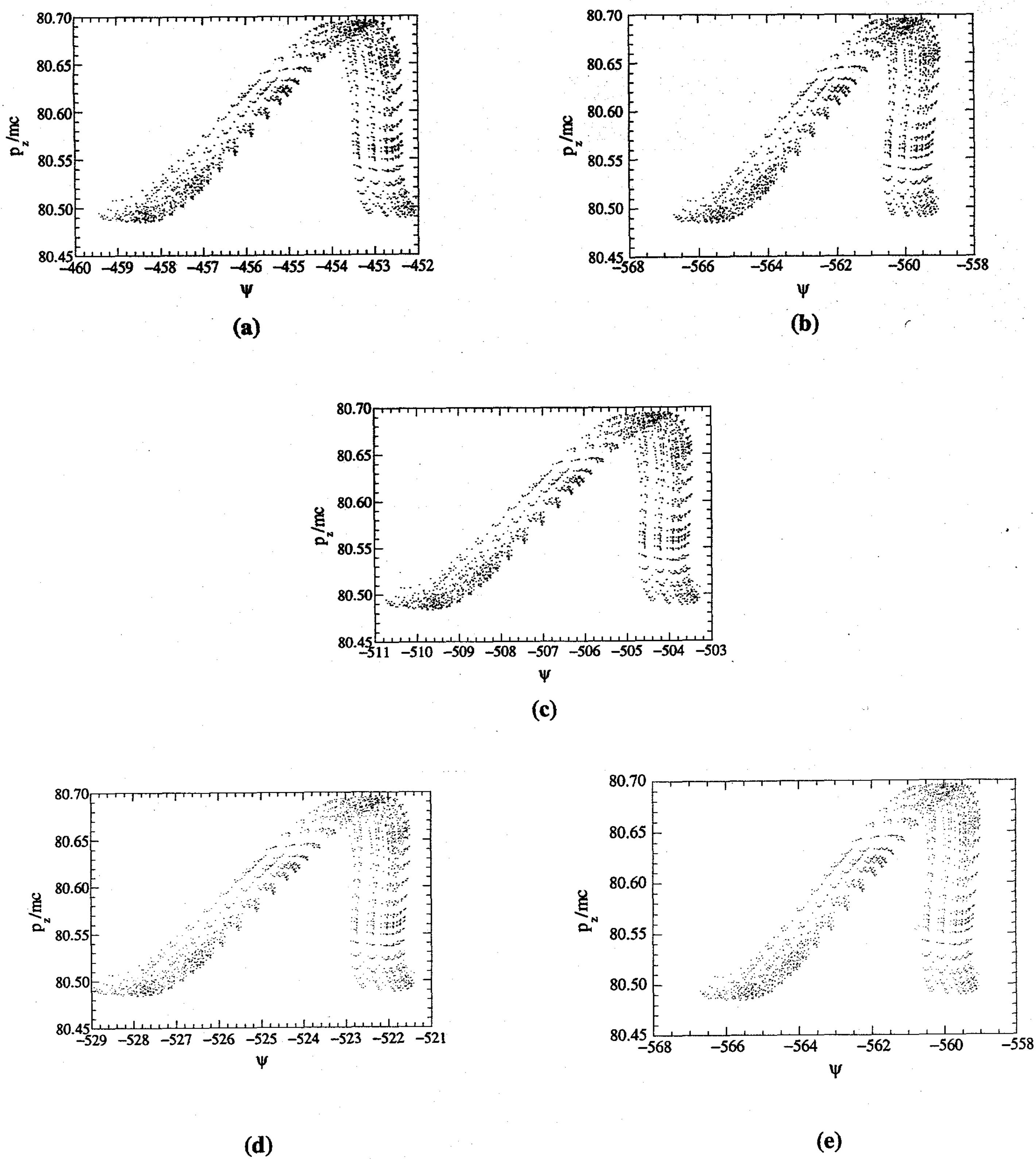

80.70
80.65
80.60
80.55
80.50
80.45
p_z/mc
−460 −459 −458 −457 −456 −455 −454 −453 −452
ψ
(a)
−568 −566 −564 −562 −560 −558
(b)
−511 −510 −509 −508 −507 −506 −505 −504 −503
(c)
−529 −528 −527 −526 −525 −524 −523 −522 −521
(d)
(e)

Figure 4.

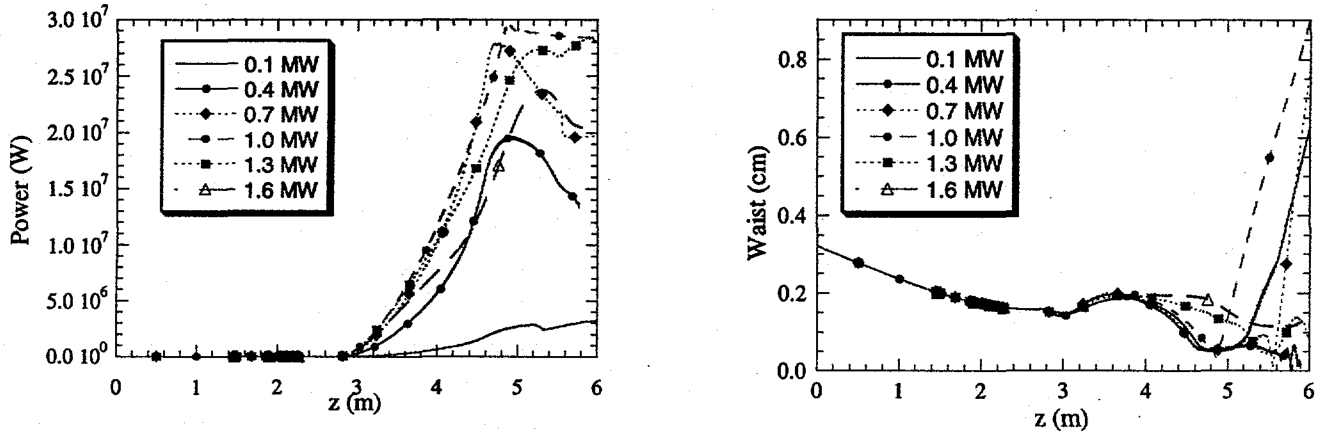

3.0 10^7
2.5 10^7
2.0 10^7
1.5 10^7
1.0 10^7
5.0 10^6
0.0 10^0
Power (W)
0.1 MW
0.4 MW
0.7 MW
1.0 MW
1.3 MW
1.6 MW
0
1
2
3
4
5
6
z (m)
0.8
0.6
0.4
0.2
0.0
Waist (cm)
0.1 MW
0.4 MW
0.7 MW
1.0 MW
1.3 MW
1.6 MW
z (m)

Figure 5. (a) (b)

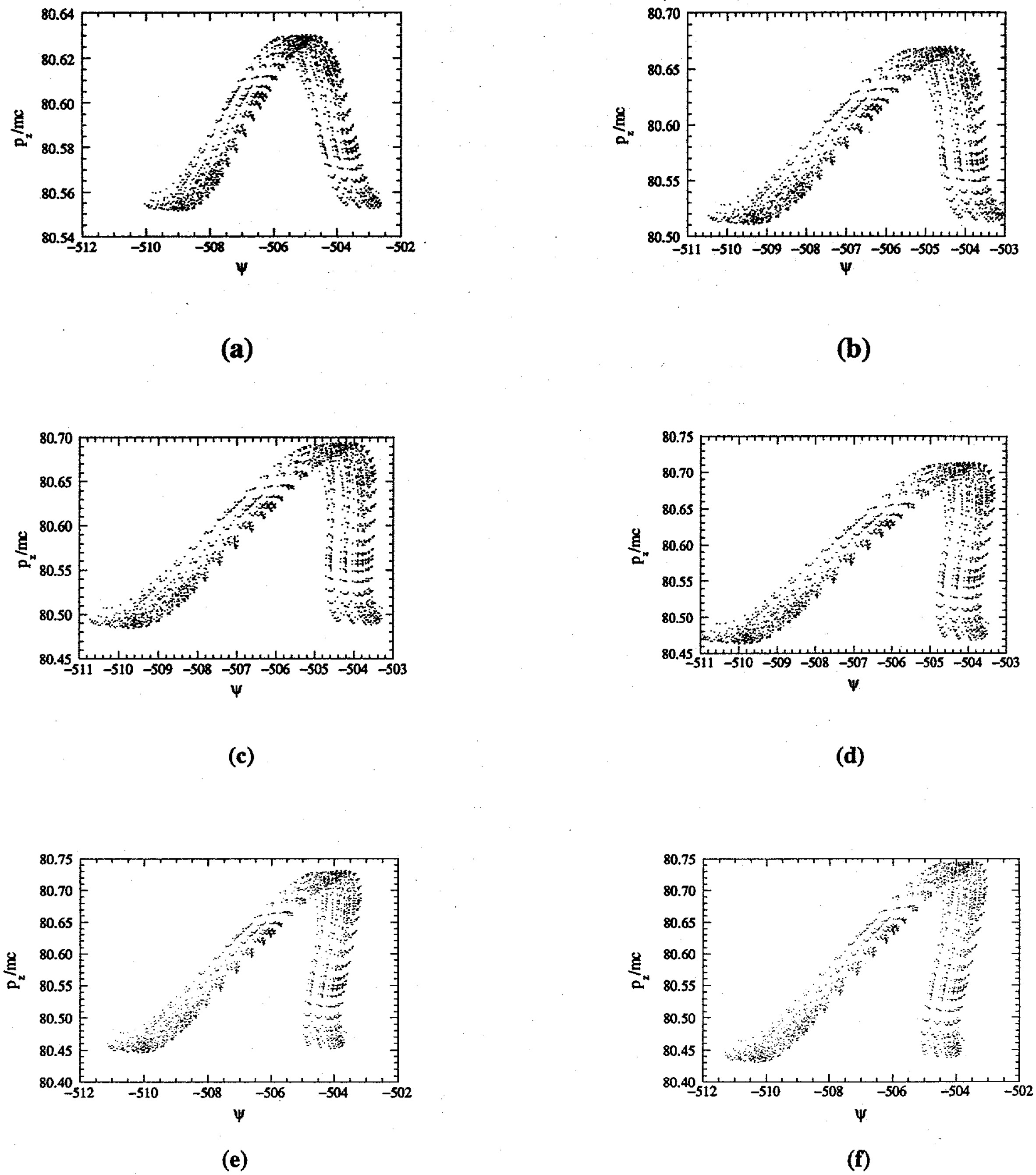


Figure 6.

LIST OF TABLES

Table 1: Electron beam parameters for HGHG

γ	82
Normalized Emittance	4 π mm mrad
Peak Current	110 A
Micropulse Length	4 ps
Energy Spread	0.043%

Table 2: CO_2 seed laser beam parameters

Wavelength	10.6 μm
Input Seed Power	0.7 MW
Pulse Length	100 ns
Sliced Pulse Length	10-100 ps
Rayleigh Range	0.76 m

Table 3: Magnet parameters

Modulative Section	
Length	0.76 m
Undulator Period	7.2 cm
Number of Periods	9
Peak Magnetic Field	0.158 T
Dispersive Section	
Length	0.30 m
Induced Dispersion	1.5 ($d\psi/d\gamma$)
Radiative Section	
Length	1.98 m
Undulator Period	3.3 cm
Number of Periods	60
Peak Magnetic Field	0.47 T
Betatron Wavelength	3.75 m