Measurements of High Gain and Intensity Fluctuations in a Self-Amplified, Spontaneous-Emission Free-Electron Laser

M. Hogan, C. Pellegrini, J. Rosenzweig, G. Travish, A. Varfolomeev,* S. Anderson, K. Bishofberger, P. Frigola, A. Murokh, N. Osmanov,* S. Reiche,† and A. Tremaine

Department of Physics and Astronomy, University of California, Los Angeles, California 90024

(Received 1 July 1997)

We report measurements of large gain for a single pass free-electron laser operating in self-amplified spontaneous emission (SASE) at 16 μm starting from noise. We also report the first observation and analysis of intensity fluctuations of the SASE radiation intensity in the high gain regime. The results are compared with theoretical predictions and simulations. [S0031-9007(97)04953-3]

PACS numbers: 41.60.Cr, 41.60.Ap

An x-ray laser would offer a unique way to explore the structure of matter at the atomic and molecular scale. Among the various schemes proposed to reach this wavelength region, the free-electron laser (FEL), operating without mirrors in a self-amplified spontaneous emission (SASE) mode, as proposed in [1], and independently in [2], offers a favorable scaling law [3]. It has also been shown [4] that utilizing state of the art linear accelerators and electron sources it is possible to build an x-ray SASE FEL, and this has led to two major proposals to build a SASE x-ray FEL, one at SLAC [5], the other at DESY [6].

The theory on which the SASE x-ray FEL is based [7–9] has been developed over many years, but the experimental data to support it are few and incomplete. Very large gain in SASE has so far been observed in the centimeter to millimeter waves [10–12] and in the medium infrared (IR) at Los Alamos [13]; recently, gain in the near IR has been observed at Orsay [14] and at Brookhaven [15]. The intensity distribution function has been previously measured only for spontaneous undulator radiation [16], with no amplification, and long bunches. In this paper we report the results of measurements, at 16 μm, of large gain and of the intensity distribution function for amplified radiation, and for a short bunch length.

When a beam traverses an undulator it emits electromagnetic (EM) radiation at the wavelength $\lambda = \lambda_u(1 + K^2/2)/2\gamma^2$ (where λ_u is the undulator period γmc^2 the beam energy, and K the undulator vector potential normalized to mc^2). If, as it is the case in SASE, there is no input EM field, radiation is emitted when the beam current is not uniform, and has a Fourier component $i(\omega)$ at $\omega = 2\pi c/\lambda$. The EM field is then proportional to $i(\omega)$ and the intensity to $|i(\omega)|^2$. If the bunch length L is much larger than λ, and the beam is generated from a thermionic cathode or photocathode $i(\omega)$, and thus the EM field and intensity are stochastic quantities characterized by a distribution function and determined by the random initial electron longitudinal distribution. The dependence of $|i(\omega)|^2$ on charge is $|i(\omega)|^2 = Q[1 + F(\omega)Q]$, where $F(\omega)$ is the bunch form factor. The intensity term quadratic in Q is what is called the coherent spontaneous emission (CSE). For $L \gg \lambda$, as in our case, and a smooth charge distribution we have $F(\omega) \ll 1$, as we will again discuss later in the paper, and we will neglect this term.

For a long undulator the EM intensity can grow exponentially along the undulator axis z as

$$I = a|i(\omega)|^2 e^{z/L_g}. \tag{1}$$

The power gain length L_g is given, in the simple 1D theory, neglecting diffraction and slippage [7,8] by $L_g = \lambda_u/4\sqrt{3}\pi\rho$, where the FEL parameter ρ is proportional to the beam plasma frequency to the power $2/3$, or $(Q/\sigma L)^{1/3}$, Q being the electron bunch charge, σ the beam cross section, and L the bunch length. Saturation occurs after about 20 gain lengths, and the radiation intensity at saturation is about ρ times beam energy. Diffraction, energy spread, and slippage $S = \lambda N_u$, can increase the gain length over the 1D value if the conditions $\varepsilon \leq \lambda/4\pi$, $\sigma_E < \rho$, $S < L$ are not satisfied, where ε is the beam emittance and N_u the number of undulator periods.

In this experiment we measure the gain length and the intensity distribution function for a SASE FEL at 16 μm. The measurements have been done using the Saturnus linac [17], consisting of a $1\frac{1}{2}$ cell Brookhaven National Laboratory photocathode RF gun, and a PWT accelerating structure [18]. The linac is followed by a beam transport line and an undulator built at the Kurchatov Institute [19], providing focusing in both transverse planes with a beta function of approximately 0.1 and 0.4 m, and with field errors of about 0.25%. The characteristics of the electron beam, the undulator, and of the undulator radiation are given in Table I. The linac operates at 5 Hz, with 2.5 μs long macropulses, and one electron bunch per macropulse. The beam transport line from linac to the undulator has steering magnets to control the beam trajectory, and beam instrumentation including slits to measure the emittance [20], an integrating current transformer (ICT), and Faraday cups to measure the beam charge, phosphor screens to measure the beam transverse profiles, and a dipole spectrometer to measure the energy and energy spread.

TABLE I. Electron beam, undulator, and FEL characteristics.

Electron Beam	
Energy (MeV)	13
Charge/bunch (nC)	0.2–0.6
Emittance (normalized rms) (mm mrad)	8–10
Energy spread (rms) (%)	0.08–0.14
Pulse length (rms) (ps)	2–3
Peak current (A)	38–83
Undulator	
Period (cm)	1.5
Number of periods	40
Peak magnetic field (T)	0.75
FEL	
Radiation wavelength (μm)	16
FEL parameter ρ	0.01
Power gain length (cm)	16

The radiation produced in the undulator is focused by mirrors on a copper doped germanium detector, cooled at liquid helium temperature, with a response time of 5 ns. Since our electron pulses are typically 5 to 8 ps long (FWHM), the detector has been calibrated using the 10 to 15 ps long radiation pulses from the Los Alamos AFEL and the Firefly FEL at the Stanford Subpicosecond FEL Laboratory, and a 60 ps long CO_2 laser pulse at the University of California at Los Angeles Mars Laboratory. The electronic noise level in the detector is of the order of 10 mV. The relationship between number of photons N_{ph} and the detector signal S_{mV} in mV is, after noise subtraction, $N_{\mathrm{ph}} = S_{\mathrm{mV}} \times 1.4 \times 10^6$.

The experiment consists of propagating a single electron bunch through the undulator, measuring the bunch charge and the IR intensity, and repeating many times to obtain the distribution of intensities for a given charge, Fig. 1. Typically, we measure 100 pulses or more within a charge interval of $\pm 2.5\%$. The electron bunch charge is varied from 0.2 to 0.6 nC by changing the laser intensity on the photocathode. The intensity of the signal from the detector is also measured when the IR radiation is blocked, to determine the noise level due to the detector and its associated electronics, and to background x-rays, Fig. 1. The charge is measured nondestructively with the ICT. The ICT noise has a mean of 7 pC, with a standard deviation of 2 pC.

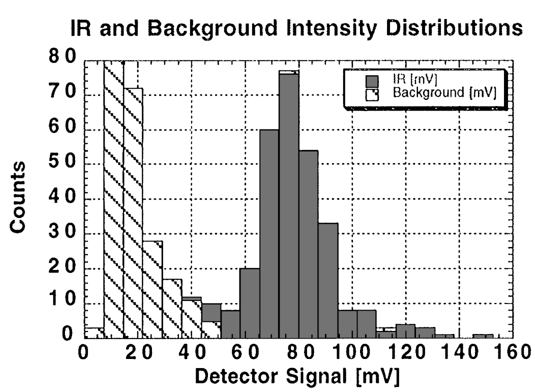

FIG. 1. Intensity distribution of the IR and background signals for a mean charge $Q = 0.56$ nC, standard deviation of 0.007 nC, IR mean = 78 mV, standard deviation = 14.3 mV; background mean = 18.7 mV, standard deviation = 9.1 mV.

The IR intensity is measured in the forward direction, within a solid angle $\Omega = 2.1 \times 10^4$, corresponding to an angle $\theta = 7.7$ mrad defined by the exit window of the beam line, and over all photon frequencies transmitted to the detector. The detector response is uniform for wavelengths from 2 to 32 μm and reduced by more than a factor of 100 outside this range. The beam line exit window and the detector window, made of KRS5, cut wavelengths shorter than 0.6 μm, and have a transmission of 70% per window for longer wavelengths, up to 30 μm. Hence in our typical measure we integrate the intensity over the undulator spectrum from 2 to 30 μm, and over the solid angle Ω defined by the exit window.

The incoherent spontaneous radiation signal [21] within this solid angle and frequency band at 0.2 nC, after reduction for the windows transmission, is $I = 6.5 \times 10^7$ photons/nC, or using the calibration of our detector, $I = 46.8$ mV/nC. The energy in the pulse at 0.2 nC is 4.9×10^6 eV, or about 8×10^{-13} J. Since the detector noise, including the amplifier, is of the order of 10 mV, we expect a signal to noise ratio of about 2 at 0.2 nC. The total background noise, x-rays plus detector, has a mean of about 18 mV over our charge range. The x-ray background is almost constant when we change the charge between 0.2 to about 0.6 nC, indicating that the x rays are mainly due to distributed background in the detector area, produced by the dark current from the electron source and not to beam losses through the undulator.

When changing the electron bunch charge the energy spread, emittance, pulse length, and beam transverse radius in the undulator can also vary. These quantities have been measured as a function of charge, and their variation is reported in Table I. The bunch length and peak current have been calculated from the energy spread and the RF phase of the bunch. The standard deviation of the error for charge, pulse length, and area are 1%, 7%, and 2% at 0.56 nC, and 3%, 7%, and 2% at 0.2 nC. The beam is focused with a quadrupole triplet through the undulator beam pipe of 4 mm inner diameter. Within our resolution we see no beam losses. Beam transport and the IR signal are optimized with the beam focused to a spot size of about 0.4 mm (FWHM) at the undulator exit and about three times larger at the entrance, for all charges.

In Fig. 1 we show the distribution of IR intensity and of detector background, for $Q = 0.56$ nC $\pm$ 2.5%. We have measured the distributions at other values of the charge, and used them to determine the mean intensity and the standard deviation versus charge. At the largest charge the measured intensity is about 2.5 times the incoherent spontaneous intensity calculated extrapolating linearly from the lowest charge.

The measured IR intensity contains photons in the third and higher harmonics and outside the coherent solid angle $\Omega_c = \pi(\lambda/\lambda_u N_u)$, where the FEL gain is very small compared with that at the first harmonic and within the coherent solid angle. Our signal to noise ratio is too small to use a monochromator to select only photons within the first harmonic, and establish the FEL gain for the coherent first harmonic. Hence we have measured at the lowest charge of 0.2 nC, the intensity of the third and higher harmonics and that outside the coherent solid angle. The experimental information has been used to evaluate, for $Q = 0.2$ nC, the intensity in the solid angle $\Omega - \Omega_c$ and at the third or higher harmonics. This has been extrapolated linearly with charge and subtracted from the measured intensity to obtain what we call the subtracted IR intensity, i.e., the intensity in the first harmonic and within the coherent solid angle. The harmonics have been measured using a CaF_2 filter that only transmits radiation with $\lambda < 10$ μm; their intensity has been found to be $5/12$ of the first harmonic, in good agreement with the calculated value. The ratio of the intensity within the coherent solid angle Ω_c to the intensity in the total solid angle Ω has been measured to be $5/12$ using an iris near the beam line exit window. Again this is close to the expected value. The mean value of the subtracted IR intensity vs charge is plotted in Fig. 2, where we have also plotted the calculated value of the intensity of the first harmonic within the coherent solid angle, $I_{1,\text{coherent}} = 13.5 Q_{\text{nC}}$ mV. The measured and calculated values are in good agreement at 0.2 nC, while at 0.56 nC the measured value is 5.6 times larger.

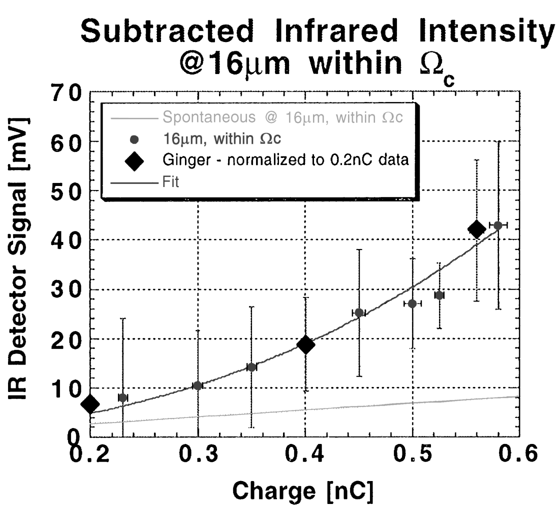

FIG. 2. First harmonic coherent IR intensity versus charge. The vertical bars are the standard deviation for the intensity fluctuations. For comparison the effect of beam charge and radius uncertainties is 9% or a standard deviation of 4 mV at 0.56 nC. The straight line is the calculated spontaneous emission intensity while the curved line is a fit to the data $I = 1.85Q \exp(4.4Q^{1/3})$. The three diamonds at 0.2, 0.4, 0.56 nC are the normalized results of simulations with the code GINGER.

The first harmonic experimental mean values in Fig. 2 can be fitted with a curve of the form $I = aQ \exp(bQ^{1/3})$, as one would expect from (1) and the theory [7,8]. The exponent $(bQ^{1/3})$ is the number of power gain lengths in the undulator. The fit gives $a = 1.85$ mV/nC, $b = 4.4$ nC$^{1/3}$, and $bQ^{1/3} = 3.7$ at $Q = 0.58$ nC, so that at the largest charge we have 3.7 power gain lengths in our system, or a power gain length of 16 cm. If we define empirically the gain for a SASE FEL considering as an input the spontaneous radiation generated in the first power gain length, which in our case is 16 cm long, we obtain for our system a gain of 21.

An alternative explanation for observing a signal larger than the incoherent spontaneous emission is the emission of coherent spontaneous radiation (CSE) [14,22], $I = aQ(1 + FQ)$, F being the bunch form factor at $\lambda = 16$ μm. Evaluating F for a Gaussian distribution gives $FQ \cong 0$. Our data show that $FQ \leq 1$ at $Q = 0.2$ nC. Using this information we cannot have a good fit to the data at large charge if we keep F constant. Moreover, if we do not match the beam through the undulator and have a different transverse size, we observe only a linear dependence of the signal on the charge, contrary to the fact that the CSE does not depend on the beam transverse size, but only on the longitudinal distribution, while the contrary is true for a SASE FEL.

The value of the FEL parameter ρ for the beam and undulator used in this experiment is $\rho \sim 0.01$, and the 1D theory gain length is about 7 cm. Inclusion of diffraction increases it to about 11 cm. The larger value that we observe could be due to slippage, which in our case is of the order of the bunch length. The code GINGER [23], which includes both diffraction effects and slippage, has been used to simulate three cases: 0.2, 0.4, and 0.58 nC (28, 64, and 81 A), keeping the same beam transverse cross sections, as in our measurements. The same numerical noise seed was used in all three GINGER runs. After normalizing the output of the simulations to the 0.2 nC data, the predicted growth rate is compared with the data (Fig. 2), and fit the data well.

We have analyzed the distribution of the IR intensity (Fig. 1) for the case $Q = 0.56$ nC, where the signal, with a mean value of 78 mV and a standard deviation of 14.3 mV, is much larger than the background, with a mean value of 18 mV and a standard deviation of 9 mV. To be sure that the fluctuations that we observe are due to the initial noise and not to system fluctuations, we evaluate the effect of changes in charge, spot size, and bunch length on the intensity, which we write as $I = aQ \exp(bQ/L\sigma)^{1/3}$. From this we have

$$\Delta I/I = \Delta Q/Q[1 + (1/3)b(Q/L\sigma)^{1/3}] - (1/3)[(\Delta\sigma/\sigma) + (\Delta L/L)][b(Q/L\sigma)^{1/3}].$$

Using the standard deviation of the error for charge, pulse length, and area, as obtained in our measurements, of 1%, 7%, and 2%, and the value 3.7 for the exponent in Fig. 2, we have $\Delta I/I \cong 9\%$, smaller than the observed intensity distribution standard deviation. Following the work of Refs. [16,21,24,25] the intensity fluctuations are expected to follow a gamma distribution with a relative standard deviation given by $1/M^{1/2}$, where

$$M = (L/L_c)(\Omega/\Omega_c),$$

and L_c is the cooperation length. Following Ref. [24] when the observed frequency spectrum is larger than the FEL line width we have $L_c = (N_{L_g})^{1/2}\lambda/[6(2\pi)^{1/2}\rho] = 0.11$ mm, where $N_{L_g} = 3.7$ is the number of power gain lengths in the undulator. Since the bunch length is $L = 2.2$ mm (FWHM), we have $L/L_c = 11.3$ and $M = 27$. If we subtract quadratically the standard deviation of the background from that of the IR distribution we obtain a standard deviation for the IR signal of about 18%, corresponding to $M \sim 30$, in qualitative agreement with our estimate. A more complete analysis of the data, using a convolution of the background and IR intensities, will be presented in a future publication.

To summarize, we have observed amplification of the spontaneous radiation, with an increase of the first harmonic intensity by 600% over the spontaneous intensity and a gain length of 16 cm. We have also measured for the first time the intensity fluctuations of the amplified radiation in the SASE mode. The analysis of the results shows a good agreement between the theory of SASE, the simulations using GINGER, and the experimental data. With experimental confirmation of the SASE theory at optical wavelengths, we can continue to extend FELs to progressively shorter wavelengths and eventually x-rays.

We wish to express our gratitude to the many people who, with their help, have made this experiment possible, in particular Herman Winick, Max Cornacchia, Rich Sheffield, Todd Smith, Ilan Ben-Zvi, Glenn Westenkow, and William Fawley.

*Permanent address: RRC Kurchatov Institute, Moscow, Russia.
†Permanent address: DESY, Hamburg, Germany.

[1] J. B. Murphy and C. Pellegrini, Nucl. Instrum. Methods Phys. Res., Sect. A **237**, 159 (1985); J. B. Murphy and C. Pellegrini, J. Opt. Soc. Am. **B2**, 259 (1985).
[2] Ya. S. Derbenev, A. M. Kondratenko, and E. L. Saldin, Nucl. Instrum. Methods Phys. Res., Sect. A **193**, 415 (1982).
[3] C. Pellegrini, Nucl. Instrum. Methods Phys. Res., Sect. A **272**, 364 (1988).
[4] C. Pellegrini, in *Proceedings of the Workshop on IV Generation Light Sources*, edited by M. Cornacchia and H. Winick (SLAC, Stanford, CA, 1992).
[5] R. Tatchin *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **375**, 274 (1996).
[6] J. Rossbach *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **375**, 269 (1996).
[7] R. Bonifacio, C. Pellegrini, and L. Narducci, Opt. Commun. **50**, 373 (1984).
[8] K.-J. Kim, Nucl. Instrum. Methods Phys. Res., Sect. A **250**, 396 (1986); J.-M. Wang and L.-H. Yu, Nucl. Instrum. Methods Phys. Res., Sect. A **250**, 484 (1986).
[9] G. T. Moore, Nucl. Instrum. Methods Phys. Res., Sect. A **239**, 19 (1985); E. T. Scharlemann, A. M. Sessler, and J. S. Wurtele, Phys. Rev. Lett. **54**, 1925 (1985); M. Xie and D. A. G. Deacon, Nucl. Instrum. Methods Phys. Res., Sect. A **250**, 426 (1986); K.-J. Kim, Phys. Rev. Lett. **57**, 1871 (1986); L.-H. Yu, S. Krinsky, and R. Gluckstern, Phys. Rev. Lett. **64**, 3011 (1990).
[10] T. Orzechowski *et al.*, Phys. Rev. Lett. **54**, 889 (1985).
[11] D. Kirkpatrick, Nucl. Instrum. Methods Phys. Res., Sect. A **285**, 43 (1989).
[12] J. Gardelle, J. Labrouch, and J. L. Rullier, Phys. Rev. Lett. **76**, 4532 (1996).
[13] R. Sheffield, J. Goldstein, and D. Nguyen, in SPIE Proceedings LASE97, San Jose California (Materials Research Society, Pittsburgh, 1997), p. 2988.
[14] R. Prazeres *et al.*, Phys. Rev. Lett. **78**, 2124 (1997).
[15] I. Benzvi (private communication).
[16] M. C. Teich, T. Tanabe, T. C. Marshall, and J. Galayda, Phys. Rev. Lett. **65**, 3393 (1990).
[17] S. C. Hartman *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **340**, 219 (1994).
[18] R. Zhang, C. Pellegrini, and R. Cooper, "Study of a Novel Compact Standing Wave RG Linac," Nucl. Instrum. Methods (to be published).
[19] A. A. Varfolomeev, Yu. P. Bouzouloukov, S. N. Ivanchenkov, A. S. Khlebnikov, N. S. Osmanov, and S. V. Tolmachev, Nucl. Instrum. Methods Phys. Res., Sect. A **359**, 85 (1995).
[20] J. Rosenzweig *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **341**, 379 (1994).
[21] K.-J. Kim, Nucl. Instrum. Methods Phys. Res., Sect. A **393**, 167 (1997).
[22] D. Bocek *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **375**, 13 (1996).
[23] W. M. Fawley (private communication).
[24] R. Bonifacio *et al.*, Phys. Rev. Lett. **73**, 70 (1994).
[25] E. L. Saldin, E. A. Schneidmiller, and M. V. Yurkov, DESY Report No. TESLA-fel 97-02 1997.