# MEASUREMENTS OF HIGH GAIN AND NOISE FLUCTUATIONS IN A SASE FREE ELECTRON LASER*

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*Abstract*

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.

## 1. INTRODUCTION

The measurements have been done using the Saturnus linac [1], consisting of a 1 1/2 cell BNL photocathode RF gun, and a PWT accelerating structure [2], followed by a beam transport line and a 1.5 cm period, 0.75 Tesla peak field, Undulator Parameter of 1, 40 period undulator built at the Kurchatov Institute [3], [4]. The undulator provides focusing in both planes. The linac operates at 5 Hz, with 2.5 μs long macropulses, and one 13 MeV electron bunch per macropulse. Steering magnets control the beam trajectory and align the beam in the undulator, slits measure the emittance [5], an Integrating Current Transformer (ICT) and Faraday cups measure the beam charge, and phosphor screens measure the beam transverse cross section. The beam can be propagated straight through the undulator, or bent through a momentum analyzer to measure the energy and energy spread.

The radiation produced by the undulator is focused by mirrors to a copper doped germanium detector cooled at liquid helium temperature. The detctor can measure the radiation produced by a single electron bunch and has a response time of about 5 ns, while our electron pulses are typically 4 to 6 ps long. The detector has been calibrated and the linearity of its response measured using the 10 picosecond long radiation pulses from the Firefly FEL at the Stanford Subpicosend FEL Laboratory. The noise level in the detector and its associated electronics is of the order of 10 mV. A detector signal of 20mV corresponds to $10^7$ photons at.

The experiment is done with an undulator of fixed length by changing the electron bunch charge from a low value (0.2nC), where we expect no or small amplification, and observe only spontaneous radiation, to a large value (0.6 nC) where we expect to see amplified spontaneous radiation. We produce one electron bunch, send it through the undulator, and measure the pulse charge and the intensity of the infrared radiation. This is repeated many times to accumulate statistics. We then repeat the experiment blocking the infrared radiation to measure the noise level due to background X-rays. The charge is measured non destructively with the ICT.

When changing the electron bunch charge other beam parameters (energy spread, emittance, pulse length, and beam transverse radius in the undulator) also change. Since all these quantities are important to understand the amplification and fluctuation properties, they have been measured independently as a function of charge. The energy spread changes from about 0.08 to 0.14% rms, when the charge changes from 0.2 to 0.58 nC, putting an upper limit to the rms bunch length of 0.64 to 0.84 mm, corresponding to a peak current (I) of 38 to 83 A. The normalized rms emittance changes from about 8 mm mrad at the lowest charge of about 0.2 nC to about 10 mm mrad at 0.58 nC. Beam losses in the 4mm inner diameter beam pipe, which can produce an X-ray background in our detector, were less than the resolution of our diagnostics. Beam transport and the IR signal were maximized 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.

In an FEL the undulator radiation emitted by the electron beam has a wavelength $\lambda=\lambda_\upsilon(1+K^2/2+\gamma^2\theta^2)/2\gamma^2$ where $\lambda_\upsilon$ is the undulator period, K the undulator deflection parameter, θ the angle with respect to the beam axis, and $\gamma mc^2$ the beam energy. The FEL theory shows that the radiation intensity can grow exponentially along the undulator axis, z, as $I_{rad}\sim\exp(z/L_g)$. In the simple 1D theory [6], [7] neglecting diffraction and slippage, the gain length ($L_g$) is proportional to the ratio of the beam peak current to the beam cross section, Σ, raised to the power 1/3.

## 2. GAIN

The gain is evaluated by comparing the SASE with the spontaneous (non amplified) undulator radiation which is linearly proportional to the charge in the bunch. Another effect which can increase the radiation intensity above the spontaneous undulator radiation level is coherent spontaneous emission, which gives an intensity proportional to the bunch form factor and to the square of the charge. Since our bunch is 1.5 - 2 mm long and our wavelength is 16μm, we expect this term to be small. Further, our intensity measurements at low charge, where we expect no FEL amplification, agree within the errors with the calculated spontaneous undulator radiation, with no discernible contributions from coherent spontaneous emission. The undulator infrared radiation (IR) is measured in the forward direction, within a solid angle Ω corresponding to an angle θ=7.7 mrad defined by the exit window of the beam line, and over all photon frequencies transmitted to the detector. The detector has a peak sensitivity between 2 and 32 μm. The KrS5 beamline exit

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*Work supported by DOE Grant DE-FG03-92ER40793

window and detector window attenuate wavelengths shorter than 0.6 μm and longer than 30 μm, but have a transmission of 70% for wavelengths in between. Hence, we integrate the intensity over the undulator spectrum within Δf=2-30 μm and over Ω defined by the exit window.

The signal we expect from non amplified spontaneous radiation within Ω and Δf after reduction for the windows attenuation, is evaluated using undulator radiation formulas. The energy in a single IR pulse is calculated to be $4.9\times10^{6}$ eV, or about $8\times10^{-13}$ J at 0.2 nC. The detector noise including its' amplifier is of the order of 10 mV, so we expect a signal to noise ratio of about 1 at 0.2 nC. X-rays hitting the detector have been minimized with lead shielding, measured while blocking the IR radiation, and have a mean value of 18 mV over our charge range. A typical background measurement is shown in Fig. 1.The almost constant X-ray background between 0.2 to about 0.6 nC indicates 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.

ICT noise corresponds to a mean charge of 7 pC with a standard deviation of 2.3 pC. The measured IR intensities have been divided in bins, corresponding to a charge interval of +/- 2.5% of the central charge value. A distribution of IR intensities for the case of an average charge of 0.56 nC is shown in Fig.1. For each charge interval we accumulate 100 events or more, determine the mean IR intensity and the standard deviation, then subtract the mean X-ray background. The mean IR intensity and standard deviation is ploted vs. charge in Fig. 2, where we have also plotted the calculated undulator radiation intensity, reduced by the windows attenuation. Again, our calculation does not include coherent spontaneous radiation, but our observations are consistent with this contribution being negligible. At 0.6 nC the measured intensity is about 2.5 times the calculated spontaneous intensity,thus showing SASE.

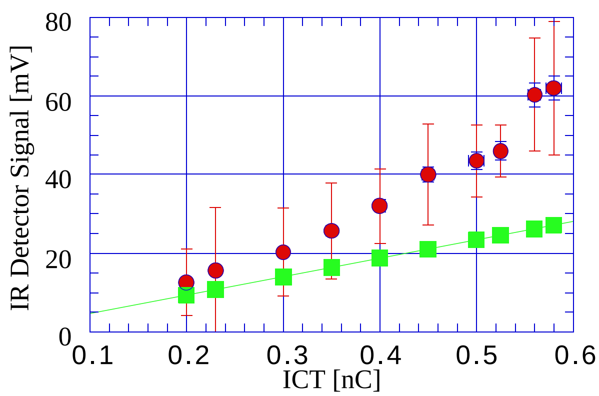


Fig. 2 IR radiation intensity vs. charge. The vertical bars are the standard deviation for the intensity fluctuations due to starting from noise. For comparison, the effect of beam charge and transverse beam size uncertainties is 4 mV at 0.56 nC. The lower line is the calculated spontaneous emission intensity.

The IR intensity in Fig. 2 contains photons in the third harmonic and outside the coherent solid angle $\Omega_c$, a region where the FEL gain is very small compared with the gain in the first harmonic and within $\Omega_c$. To establish the FEL gain for the coherent first harmonic we have measured at the lowest charge of 0.2 nC, the intensity of the third harmonic and the change in intensity when reducing the solid angle to $\Omega_c$. The third harmonic has been measured using a CAF2 filter that does not transmit radiation above 10 μm; the filtered intensity was ~5/12 of the total intensity. The ratio of the intensity within the coherent solid angle, $\Omega_c$ and in the total solid angle, Ω, has been measured to be ~1/2 using an iris near the beamline exit window to reduce the solid angle. We have used this experimental information to evaluate the intensity in Ω at the third harmonic, plus that of the first harmonic outside Ωc. These radiation components can be extrapolated linearly with charge (if we assume that they are not amplified), and subtracted from the measured value leaving only the first harmonic within $\Omega_c$. The result, along with the calculated value for the spontaneous first harmonic within $\Omega_c$, is plotted in Fig. 3. The ratio of the first harmonic intensity, 42.7 mV, measured at a charge of 0.58 nC, to the extrapolated spontaneous first harmonic at the same charge, 7.5 mV, is about 5.6.

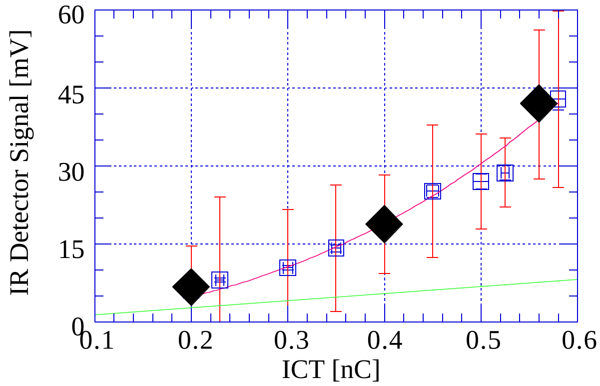


Fig. 3 First harmonic coherent IR vs. charge. The vertical bars are the standard deviaion for the intensity fluctuations due to starting from noise. For comparison, the effect of beam charge and transverse beam size uncertainties is 4 mV at 0.56 nC. The lower line is the calculated spontaneous emission intensity. The curve fit to the data is $IR = 1.85 \times ICT\exp(4.4ICT^{1/3})$. The three diamonds at 0.2, 0.4, 0.6 nC are the results of simulations with the code Ginger, normalized to fit the data point at 0.2nC.

The first harmonic experimental points in Fig. 3 are fitted with a curve of the form:

$$I=\alpha Q\exp(\Gamma(Q/\Sigma)^{1/3}) \qquad (1)$$

which gives an intensity proportional to the charge (Q) for low beam brightness, when we expect to recover the spontaneous radiation limit, and growing exponentially with $Q^{1/3}$ for large electron beam brightness, as one would expect from a 1-D FEL theory [6], [7]. The fit gives an exponent of 3.7 at 0.58 nC indicating that at the largest charge we have about 3.7 power gain lengths in our system. The value of the FEL parameter ρ for the beam and undulator used in this experiment is ρ ~0.01, and the gain length evaluated from this value in the 1-D theory is about 7 cm. When including 3-D effects but no slippage this increases to about 11 cm. The larger gain length we observe is due to the slippage, defined for a bunch length $\sigma_z$ as $\lambda N_u/\sigma_z$, which is of order one. The code Ginger [8], which includes both 3D effects and slippage, has been used to simulate three cases: 0.2. 0.4, and 0.58 nC (38, 64, and 83A), while keeping the same beam transverse cross sections. The results have been normalized to fit the experimental point at 0.2 nC to take into account experimental effects like the attenuation from the windows. The normalized results are shown in Fig. 3 and fit the data well.

## 3. FLUCTUATIONS

We observe output intensity fluctuations due to starting from noise. In the case of no gain the IR power will scale linearly with charge, and does not depend on other beam parameters. When there is gain, a change in charge, Q, will lead to a change in output power which we can evaluate using (1). A maximum gain of 5 would give a maximum change in the IR intensity of 4% for $\Delta Q/Q$= +/- 2.5%. The beam transverse area, $\Sigma$, at the undulator exit has been observed to change by about +/-10%. Since the gain changes as $\Sigma^{-1/3}$ in the exponent, we can expect a change in IR intensity of ~5%. The combined error due to uncertainties in Q and $\Sigma$ is +/-6.4%. The much larger power fluctuations, due to starting from noise, are about 34% at 0.56 nC and 39% at 0.58 nC. Following the work of [9], [10], [11] the intensity fluctuations are expected to follow a distribution with a relative standard deviation given by $M^{1/2,}$ where M is qualitatively the number of degrees of freedom, or modes in the radiation pulse: $M=(T/\tau_c)(\Omega/\Omega_c)$. T is the time over which the radiation is measured, $\tau_c=(\lambda/c)(\Delta\lambda/\lambda)$ the correlation time, and $\Omega$ , $\Omega_c$ the solid angles already discussed. Since in our experiment most of the radiation is in the first harmonic we evaluate $\Delta\lambda/\lambda$ to be approximately $1/N_u$, giving $\tau_c \cong$ 2ps. The time T is given in our experiment by the electron pulse length, which at the largest charge is about 2 mm (FWHM) or about 6.6 ps. The value of M is then $M \cong 8$ giving an expected width of the fluctuations of about 35%. A Gamma Probability Distribution Function with M=11 fits the IR intensity at high charge (shown in Fig. 4) and give a relative standard deviation of 30%. Although this value of M is somewhat larger than that given by the simple expression above, it is still in qualitative agreement with the data. A more complete analysis of the data, using a convolution of the X-ray background and IR intensity distributions, will be presented in a future publication.

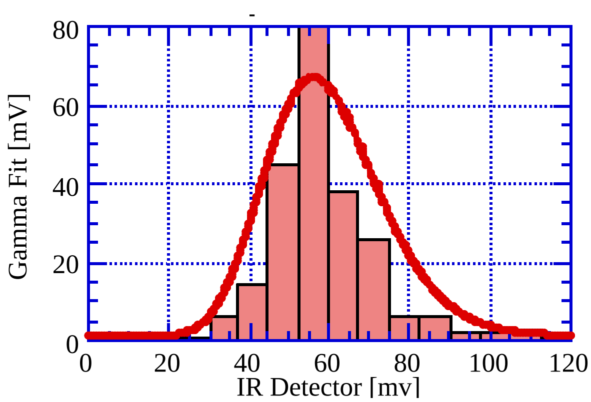


Fig. 3 Distribution of IR Detector Signals for a mean charge of 0.52 nC +/- 5% fitted with a Gamma Probability Distribution Function corresponding to M = 11.

To summarize, we have observed amplification of the spontaneous radiation, with an increase of the first harmonic intensity by 600% over the spontaneous intensity. We have also observed for the first time the intensity fluctuations of the output amplified radiation. Analysis of the data shows a good agreement with the analytic theory of SASE, the 3D time dependent Ginger simulations, and the experimental results.


## 4. ACKNOWLEDGMENTS

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


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