SLAC–PUB–6985
August 1995

Observation of SASE at 47 μm*

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Abstract

Coherent, far-infrared undulator radiation from sub-picosecond electron pulses has been observed at the Stanford SUNSHINE facility. Measured intensities exceed theoretical prediction for spontaneous radiation by more than an order of magnitude. The forward-radiated energy from a 16MeV electron beam travelling in a single pass through an undulator with a strength parameter $K = 0.6$ grows exponentially and is consistent with predictions of Self-Amplified Spontaneous Emission (SASE) with a gain length of 45.4cm or 5.9 undulator periods.

*Presented at The 17th International Free Electron Laser Conference
New York, New York, August 21-25, 1995*

*Work supported by Department of Energy contract DE–AC03–76SF00515.

1 Introduction

Exponential growth of self-amplified spontaneous emission (SASE) is predicted to occur under certain beam conditions when an electron beam passing through an undulator self-bunches due to interaction with its own radiation field [1, 2, 3, 4, 5]. Although theories and simulation codes generally assume long electron bunches compared to the radiation wavelength, it has been pointed out that SASE effects may also be observable for shorter electron pulses [6, 7]. In this paper the observation of exponential growth of far-infrared radiation emitted by sub-picosecond electron pulses along the length of an undulator at the Stanford SUNSHINE facility [8, 9] will be described.

2 Experimental Setup

Experiments have been conducted at the SUNSHINE facility (consisting of an rf-gun with a thermionic cathode, an alpha magnet for bunch compression and a 30MeV S-band linear accelerator) tuned to produce electron macropulses containing a train of about 2500 electron microbunches of energy 16MeV ($\gamma_0 = 31.3$) and average intensity of 1.8×10^8 electrons per microbunch at an interval between microbunches of 350ps. The electron beam was guided through a 26-period, linearly polarized, permanent-magnet undulator of period length $\lambda_{\mathrm{u}} = 7.7$cm. By varying the undulator gap, the strength parameter K could be adjusted from 0.3 to 3.2.

Figure 1 shows schematically the experimental setup. Upstream of the undulator, a Michelson interferometer (M1) collecting coherent transition radiation was used to measure through an autocorrelation method the average microbunch pulse length [9]. For the running conditions in this experiment the average electron bunch length was between 180μm (assuming a gaussian bunch distribution) and 240μm (assuming a rectangular bunch distribution). The associated radiation spectrum indicates that the electron distribution is closer to be rectangular than gaussian. Downstream from the undulator two Al foils could be inserted into the beamline. The first foil was used as a mirror to deflect the forward-radiated energy by 90^0 onto a room-temperature pyroelectric bolometer B1 of radius 2.5mm located 30cm from the end of the undulator. The second foil was used to deflect the undulator radiation into a Michelson interferometer (M2) to measure the frequency spectrum.

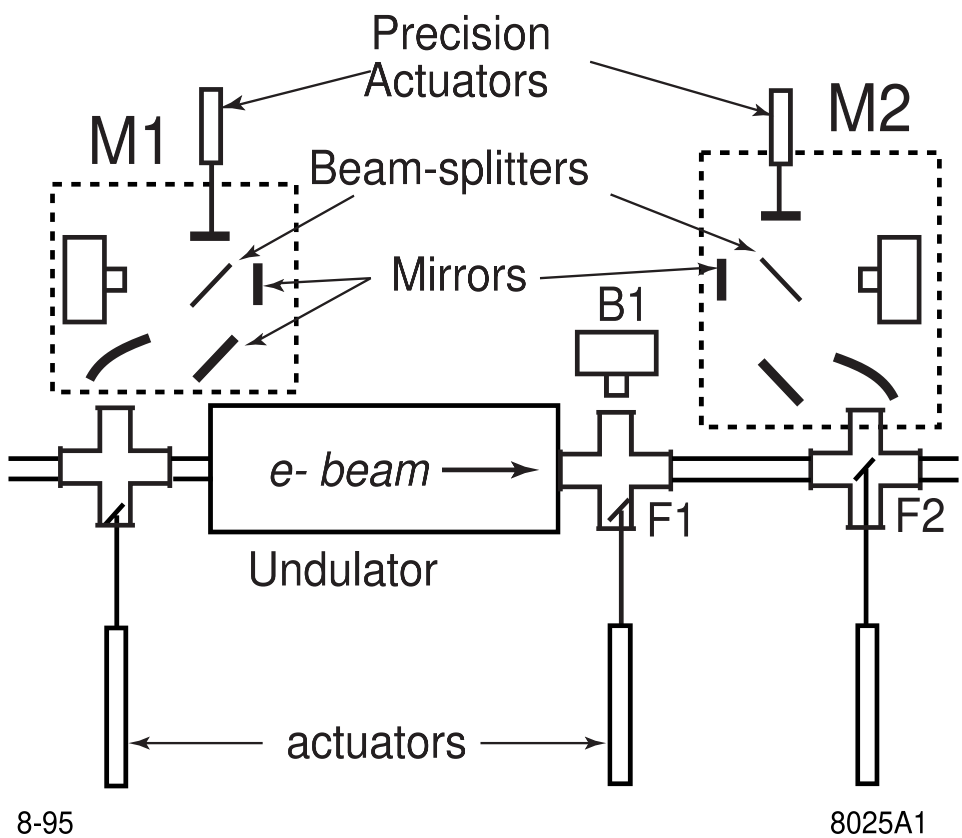

Figure 1: Experimental setup (schematically) used to measure the electron bunch length, the forward undulator radiation energy and the radiation spectrum.

3 Experimental Results

The forward coherent radiation energy was measured as a function of the undulator strength parameter K. The solid angle acceptance of the bolometer in the Michelson interferometer was much smaller than the expected central radiation cone defined by $(\gamma\sqrt{N})^{-1}$ where N is the number of undulator periods. This allows an accurate and quantitative comparison of measured coherent radiation energy with that expected from well established undulator theory [10] for a given bunch length. The fundamental undulator radiation wavelength could be varied from about 45 μm to 200-μm. Consistently, the measured radiation energy per macropulse exceeded the expected value by more than one order of magnitude (Fig. 2).

To account for this excess energy, several causes other than SASE were considered. The absolute calibration of the bolometer was compared with a radiation normal and found to be correct. Higher radiation intensities could be expected if the electron bunches are actually shorter than indicated from measurements, but the magnitude of observed radiation could then only be explained with the unrealistic assumption of zero length bunches. Even then, still significantly higher intensities were observed at wavelength longer than 100 μm (Fig. 2). A vanishingly short bunch length is not a realistic

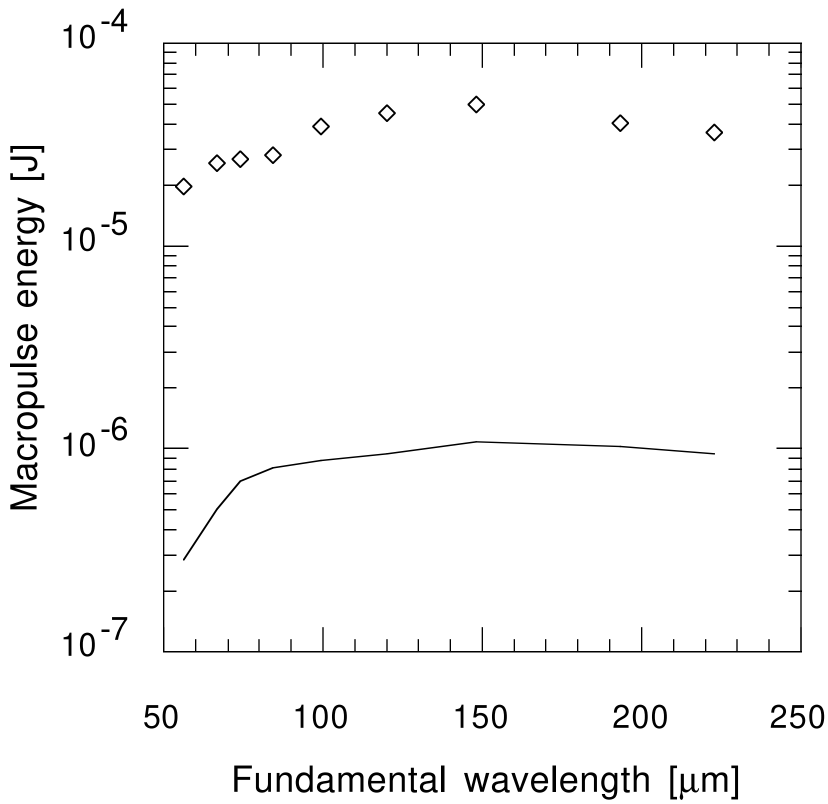

Figure 2: Radiation energy at the fundamental wavelength compared with expected spontaneous coherent undulator radiation (solid line).

assumption and not consistent with the finite broad band spectrum from transition radiation. That leaves SASE as another candidate to explain the enhancement of radiation intensity over expected coherent intensity. If SASE were the explanation, an exponential growth of radiation intensity should be observable along the length of the undulator. To measure this, ferromagnetic, thin plates were inserted on the surface of permanent magnet poles to shunt out the magnetic field. The magnetic field at the electron beam was thereby reduced from 800G to about 30G. By covering a varying number of magnet poles at the downstream end of the undulator, the effective undulator length could be varied.

Observing the energy spectrum with the Michelson interferometer (M2), the undulator radiation could be distinguished from other potential sources like transition or synchrotron radiation [11]. This was particularly easy because the fundamental undulator radiation wavelength during this experiment was much shorter than the shortest measurable wavelength in the transition radiation spectrum. The radiation spectrum was then measured for 26 periods, then for 22, 19, 16 and finally again for 26 undulator periods. To change the undulator length the accelerator had to be turned off briefly for access to the radiation tunnel and then turned on again while carefully reproducing the electron beam parameters. To facilitate the insertion of ferromagnetic plates into the undulator, the gap was wide open and the strength parameter was $K = 0.6$. The electron beam energy was adjusted to 16MeV to generate 47μm radiation.

Approximately 17μJ of energy per macropulse was collected in bolometer B1. The measured energy can be compared with that expected from spontaneous, coherent undulator radiation. Considering the variation in the solid angle accepted by the bolometer from radiation source points at different distances along the undulator axis, the effective acceptance of bolometer B1 was 2.9×10^{-5} steradian for the full undulator. Rectangular bunches of length $L = 240\mu$m have a form factor $|f(\lambda)|^2 = \left(\frac{\sin(\frac{\pi}{\lambda}L)}{\frac{\pi}{\lambda}L}\right)^2$. Setting the trigonometric function equal to unity, the maximum value of the form factor is $\left(\frac{\lambda}{\pi L}\right)^2 = 0.004$ at $\lambda = 47\mu$m. Gaussian bunches have a form factor many orders of magnitude less than this. For such a rectangular bunch the calculated forward energy per solid angle per electron is 1.91×10^{-19} J/steradian, $N_{\mathrm{e}}^2 = 8.1 \times 10^{19}$ for the whole macropulse, and a total radiation energy into the acceptance of the bolometer of only 1.8μJ is expected if the signal were due to spontaneous coherent undulator radiation alone.

To identify exponential growth the undulator spectrum obtained from

M2 was integrated and the resulting radiation energy plotted against the effective undulator length in Fig. 3. The exponential growth is obvious. If the radiation had been spontaneous coherent undulator radiation measurements alone the dotted line would be expected. The data points have been fitted with a theoretical expression [5] for the radiation fields of undulator radiation including spontaneous coherent and incoherent radiation as well as stimulated radiation covering small and high gain SASE. A more detailed discussion of the comparison of measurements with theory can be found in [11]. An excellent fit is obtained for a Pierce parameter of $\rho_{\rm fit} = 7.8 \times 10^{-3}$, implying an exponential gain length (defined as $\frac{1}{4\pi\sqrt{3}\rho}$) of 45.4cm or 5.9 undulator periods. This can be compared with the theoretically expected value of ρ. Beam optics simulations give an average electron beam cross section of $(1-5) \times 10^{-6}\,\mathrm{m}^2$ within the undulator, depending on the focusing into the undulator. Using these beam cross sections and a measured bunch length of $L = 240\mu$m the theoretical value of the Pierce parameter is $\rho = (9 \pm 2) \times 10^{-3}$, which is somewhat larger than the experimental value. A possible explanation of this discrepancy is that the slippage of the light from the electron bunch reduces the effectiveness of the SASE process, resulting in a slower increase of radiated energy (i.e. smaller value of ρ) than is predicted by the analytical theory used here.

4 Discussion

The experimental conditions are only partly consistent with theoretical assumptions. The normalized beam emittance for this rf-gun has been determined earlier [12] to be about $\epsilon_n = 20\pi$mm mrad which is less than the diffraction limited emittance. The full beam energy spread in each microbunch is estimated to be within 3% and the rms peak beam current for all microbunches was 36Amp. Existing theoretical models are particularly strained by some of the experimental conditions considering that the electron bunch length was only about five times as long as the radiation wavelength. This situation, where significant slippage occurs, will be further explored by measuring the nature of growth along the undulator for longer wavelength up to 200μm. Growth similar to that observed at 47μm is expected because the total radiation energy in the forward direction has been observed to be more than one order of magnitude greater than expected from coherent undulator radiation.

Extrapolating the measured points in Fig. 3 to $N = 0$ defines the effec-

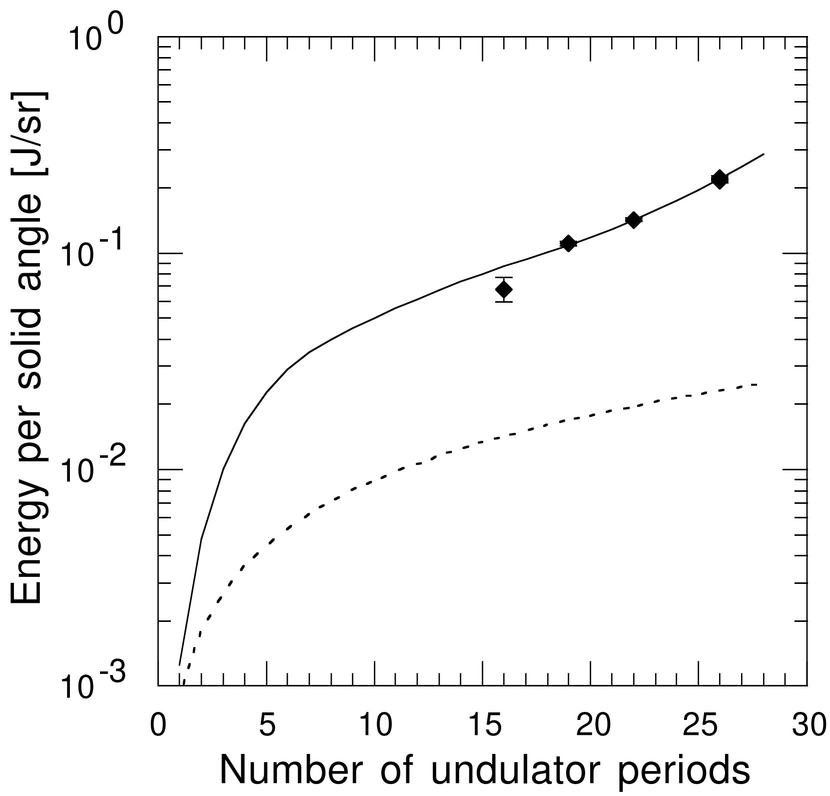

Figure 3: Measured radiation energy at $47\,\mu$m with fit by an exponential growth theory (solid line) and compared with ordinary coherent enhancement (dashed line).

tive noise power from which SASE develops. The magnitude of this power is rather high in this experiment which could be due to some spikelike nonuniformities in the particle distribution. These nonuniformities would, however, have to be reproducible. The radiation signals at the SUNSHINE facility are very stable from pulse to pulse or day to day which is not to be expected for random spikes in the particle distribution. A more probable explanation is that the steep rise and fall of the particle distribution at the beginning and end of the short, sub-picosecond electron bunches generate a rich coherent spectrum from which SASE can develop. These steep variations of particle densities are the product of magnetic bunch compression.

5 Summary

In summary, we have observed 47 μm undulator radiation that is consistent with the exponential gain prediction of SASE theory, and is not consistent with ordinary coherent enhancement. The energy increases exponentially with undulator length, and the total energy is an order of magnitude greater than is expected from ordinary coherent undulator radiation. We conclude that we have observed SASE at 47 μm from sub-picosecond electron bunches.

Acknowledgements

The authors gratefully acknowledge stimulating and clarifying discussions on the physics and interpretation of SASE with R. Bonifacio, R. Carr, S. Krinsky, H.D. Nuhn, and L. H. Yu. We also express our thanks to M. Hernandez, J. Sebek, and J.R. Troxel for technical assistance and the administration and staff of the Hansen Experimental Physics Laboratory, where SUNSHINE is located, for their support.

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