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Observation of Coherent Undulator Radiation from Sub-Picosecond Electron Pulses*

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Abstract

The generation and observation of high-power, coherent, far-infrared undulator radiation from sub-picosecond electron bunches at the SUNSHINE facility is reported. Coherent undulator radiation tunable from 50 to 200 µm wavelength is demonstrated. Measurements of the energy (up to 1.7 mJ per 1 µs macropulse), frequency spectrum, and spatial distribution of the radiation are reported. Apparent exponential growth of the radiated energy as a function of undulator length is observed.

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INTRODUCTION

The generation of relativistic, sub-picosecond electron pulses allows the direct production of high-power, coherent, narrow-band, far-infrared radiation by passing the electron beam through a magnetic undulator (1). This provides a reliable and easily tunable source of far-infrared (FIR) radiation for scientific applications, without the need for an optical cavity. The Stanford UNiversity SHort INtense Electron-source (SUNSHINE) is a facility producing sub-picosecond electron pulses for the generation of coherent FIR, as described elsewhere in these proceedings (2). This paper reports the observation of coherent far-infrared undulator radiation at the SUNSHINE facility.

Phase coherence in radiation, such as occurs from bunches shorter than the radiated wavelength, leads to an increase in radiated energy as given by the form factor (3)

$$f(k) = \left| \frac{1}{N_e} \sum_{j=1}^{N_e} e^{ikz_j} \right|^2, \tag{1}$$

where the z_j are the longitudinal positions of the particles and N_e is the total number of particles in the bunch. The coherent energy is then

$$E_{coh}(k) = N_e^2 f(k) E_{1e}(k), \tag{2}$$

where $E_{1e}(k)$ is the energy radiated by a single particle. The total energy radiated by a single electron of energy γmc^2 traversing an undulator is (4)

$$E_{1e} = \frac{N_u q_e^2}{6\varepsilon_0} \frac{2\pi}{\lambda_u} K^2 \gamma^2, \tag{3}$$

where N_u is the number of undulator periods, λ_u is the period length, and K is the undulator strength parameter.

Typical parameters for the generation of coherent undulator radiation at SUNSHINE are N_u = 26, $K = 1$, $\lambda_u = 0.077\mathrm{m}$, and $\gamma = 31$, so Eq. (3) gives $E_{1e} = 10^{-21}\mathrm{J}$. If a microbunch of $N_e = 2 \times 10^8$ electrons can be created with a form factor $f(k)$ near its maximum value of one, then the coherent enhancement from

Eq. (2) means $40\mu J$ will be radiated, which is 8% of energy of the microbunch. The possibility of such radiation efficiency motivates the experimental investigation reported here.

EXPERIMENTAL SETUP

The SUNSHINE facility has been described in detail elsewhere (5,6). In brief, it consists of an S-band thermionic rf gun, alpha magnet with energy collimation, a linac (phased to give 16 Mev beam energy in this experiment), and a 26-period, linearly-polarized, permanent-magnet undulator. Figure 1 shows the setup. Mechanical actuators allow foils to be inserted into the beamline to generate coherent transition radiation for bunch-length measurement (7,8) and to reflect out the coherent undulator radiation. A Michelson interferometer (M1) measures the electron bunch length before the undulator. A bolometer after the undulator measures the undulator radiation energy and spatial distribution. Another Michelson interferometer (M2) measures the frequency spectrum of the undulator radiation.

Typical parameters of the electron beam as adjusted for this experiment appear in Table 1. The estimated energy spread of the micropulse is the full width allowed through the energy collimator, and includes the energy-time correlation (energy slew) used to produce sub-picosecond bunches. The emittance is estimated from previous measurements (9).

All measurements of radiation in this experiment were made using room-temperature pyroelectric bolometers (Molectron P1-65). This was possible primarily because of the high intensity of the coherent radiation, and additionally because the bolometer electronics integrated over the entire 1µs macropulse. Thus the radiation measurements represent the contributions of the entire macropulse.

TABLE 1. Typical electron beam parameters giving coherent undulator radiation.

Parameter	Value	Units
Macropulse rate	10	Hz
Macropulse duration	1	µs
Microbunch rate	2856	MHz
Microbunch duration	0.8	ps full width
Microbunch population	2×10^{8}	electrons
Microbunch energy	16	Mev
Estimated micropulse energy spread/slew	3	% full width
Estimated normalized emittance	20π	mm-mradian

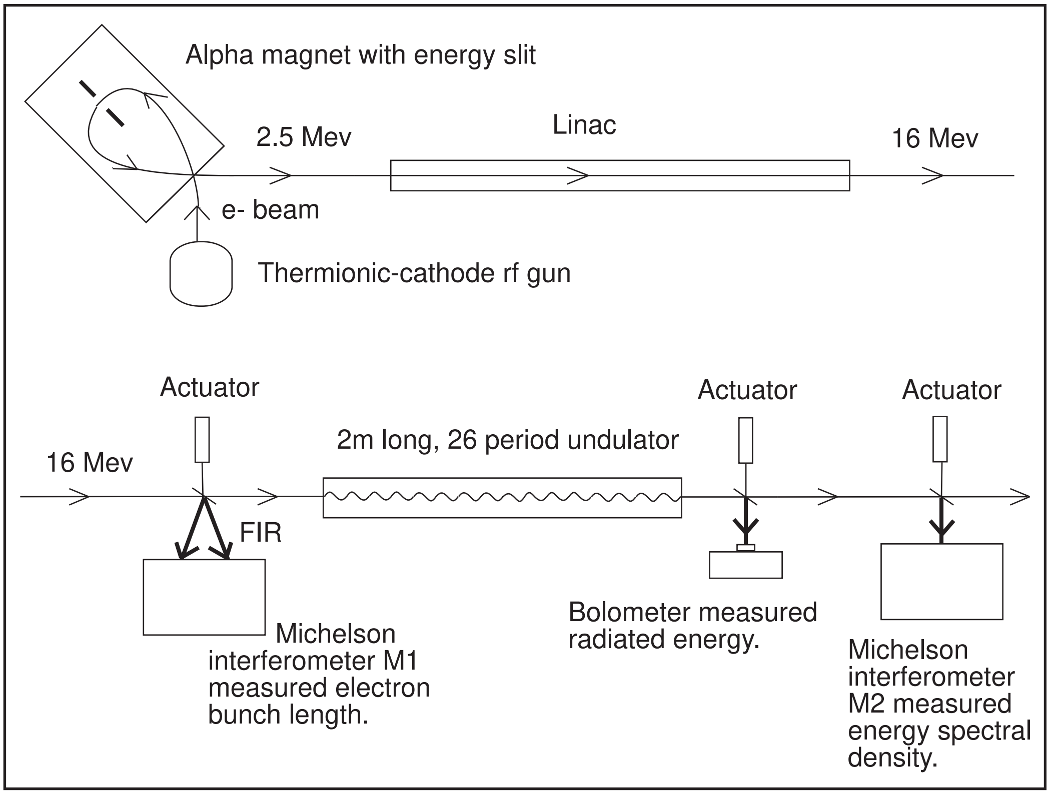

FIGURE 1. Schematic of experimental setup.

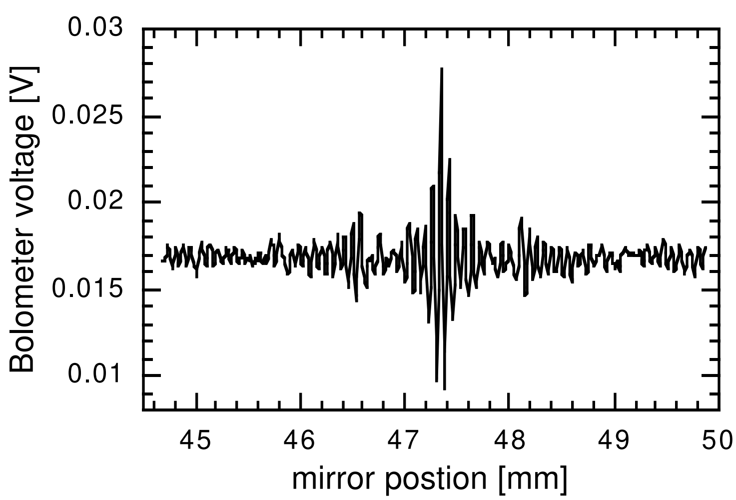

FIGURE 2. Example interferogram of 160μm radiation.

MEASUREMENTS AND DISCUSSION

Measurements at 200μm

The investigation of coherent undulator radition was begun by setting the undulator strength to its maximum value K=3.2. (This limit was imposed by the one inch external diameter of the wiggler chamber.) This was done to generate radiation at long wavelengths, where the most coherent enhancement was expected. The electron beam was tuned to optimize the total radiated energy collected in a copper condensing cone. The result was a bolometer voltage of 1.7 volts. This corresponds to 1mJ per macropulse if the factory calibration is assumed for the bolometer (1.7 volt/mJ with the electronics used). A measurement of the average power was done using a Scientech laser power meter (thermopile), which was itself calibrated by inputting a known amount of electrical power. This gave a bolometer calibration of 1.9V/mJ, implying 0.9mJ/macropulse collected in the cone.

The frequency spectrum of the radiation was measured in Michelson interferometer M2. As the path length of one arm of the interferometer is varied the interferometer generates the interferogram of the radiation pulse. The interferogram is the autocorrelation offset by a constant; the power spectrum is the Fourier transform of the autocorrelation. Figure 2 shows a measured interferogram indicating that coherent undulator radiation was being produced. The coherence of the radiation was verified in two ways. The cross correlation (10.5 cm path difference in M2) of radiation from each micropulse with that from the neighboring micropulse was demonstrated, and the radiated energy as a function of beam current was measured. (The high energy scraper in the alpha magnet was used to reduce the beam current.) The radiated energy varied as the square of the charge, as shown in Figure 3.

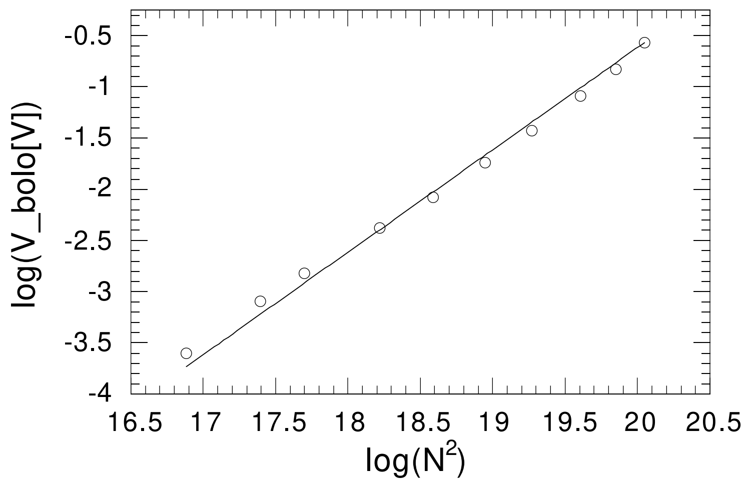

FIGURE 3. Measured undulator radiation as a function of number of particles squared. The fit line of slope one shows what is expected for coherent radiation.

The spatial distribution of the radiation was measured by installing the bolometer on a translation stage and recording the bolometer voltage as a function of position. For this measurement, the bolometer was located 1.7m from the center of the undulator. The measured spatial distribution is shown in Figure 4, and corresponds to a total energy of 1.7mJ per macropulse. There appears to be a sharply peaked central cone of radiation with a base of 1cm diameter surrounded by a more slowly varying background. The sharpness of the central spike is noteworthy, as the coherent enhancement was expected to apply to the longer wavelengths that appear off-axis in undulator radiation, giving a more slowly varying distribution than measured. The pattern goes to zero outside the aperture of the polyethylene vacuum window. The meaning of this distribution is still under investigation; the measurement may be affected by radiation reflected from the inner surface of the undulator chamber, diffraction from the foil used to reflect the light, the size of the electron beam, and perhaps other factors.

The magnitude of radiation is larger than expected. When the bolometer was located at the peak, it detected 125μJ of radiated energy per macropulse. The bolometer has an active surface radius of 2.5mm. Since it was located only 0.7m from an undulator of length 2m, the angular acceptance depended on the location of the source point in the undulator. For example, the bolometer accepted 0.9 milliradian from the beginning of the undulator and 3.6 milliradians from the

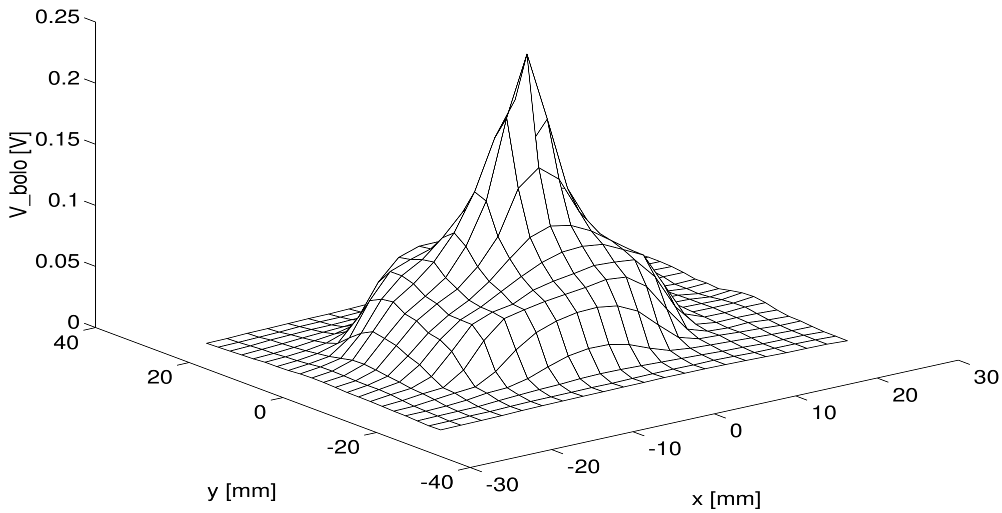

FIGURE 4. Measured spatial distribution of undulator radiation 1.7m from the center of the undulator.

downstream end. The average solid angle accepted by a bolometer of radius r located at distance D from the dowstream end of an undulator of length L is

$$\langle d\Omega \rangle = \frac{\pi r^2}{D(D+L)}, \tag{4}$$

which gives 1×10^{-5} steradian here.

The energy per solid angle radiated in the forward direction from a single electron of energy γ (4), after integrating about the fundamental frequency k_0, is

$$\left(\frac{dU}{d\Omega}\right)_{1e} = \alpha N_u \hbar c k_0 \gamma^2 \frac{K^2}{(1+K^2/2)^2}[JJ]^2, \tag{5}$$

where

$$JJ = J_0\left(\frac{K^2}{4\left(1+K^2/2\right)}\right) - J_1\left(\frac{K^2}{4\left(1+K^2/2\right)}\right). \tag{6}$$

Putting in the numbers gives 2.3×10^{-20} J/steradian radiated at 200μm by one electron. But using 1×10^{-5} steradian acceptance and the coherent enhancement of Eq. (2) with a measured $N_e^2 = 1.2 \times 10^{20}$ for the macropulse gives an expected

28μJ multiplied by $f(k)$; it requires $f(k) = 4.5$ to match the measurement. Yet by definition, $f(k) \leq 1$. This discepancy is not yet understood.

The bunch length was measured using Michelson interferometer M1, and was found to be 240μm if a rectangular bunch is assumed, giving a form factor of

$$f(k) = \left[\frac{\sin(\pi L_b / \lambda)}{\pi L_b / \lambda}\right]^2 = \left[\frac{\sin(\pi 240/200)}{\pi 240/200}\right]^2 = 0.02, \tag{7}$$

implying that the measured energy is two orders of magnitude greater than expected from the theory.

The next direction of investigation was to adjust the undulator to achieve the shortest radiated wavelength measurable in M2. The wavelength of the radiation as a function of undulator strength parameter appears in Figure 5. The wavelength follows the expected form

$$\lambda_0 = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right), \tag{8}$$

with a fit $\gamma mc^2 = 17$ Mev agreeing well with the measured 16 ± 2 Mev.

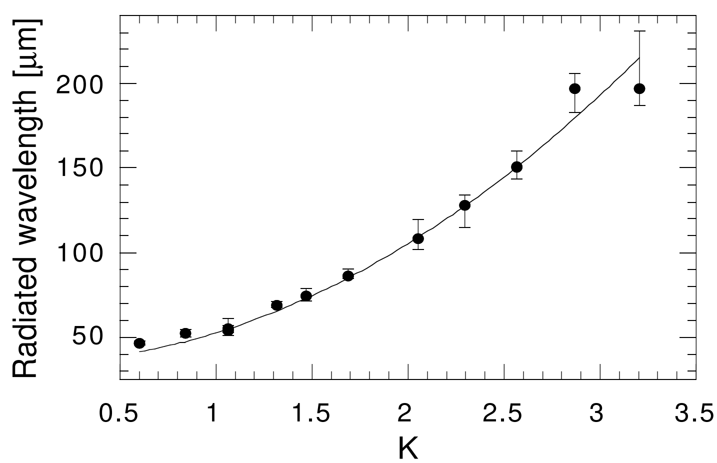

FIGURE 5. Radiated wavelength vs. undulator strength parameter, fit by the resonance equation.

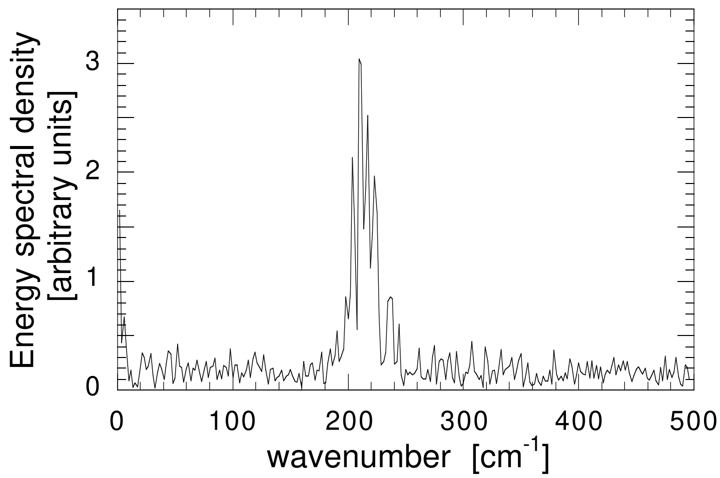

FIGURE 6. Measured spectrum of 47μm undulator radiation.

Measurements at 47μm

With the undulator strength set to K=0.6, radiation at 47μm (wavenumber 215cm^{-1}) was generated. The power spectrum of the radiation is shown in Figure 6. Atmospheric absorption, primarily due to water vapor, causes the ragged appearance of the spectrum. The spectrum is somewhat wider than is expected from the 26-period undulator; this may be due to the large energy spread over the macropulse. (Because the rf gun starts emitting before the linac is filled with rf, the energy increases at the beginning of the macropulse; because of transient beam-loading, the energy decreases at the end of the macropulse.)

17μJ forward energy was measured with a bolometer located 0.3m from the dowstream end of the undulator; the angular acceptance defined in Eq. (4) was 2.9×10^{-5} steradian and $N_e^2 = 8\times10^{19}$ for the macropulse. With

$$f(k) = \left[\frac{\sin(\pi L_b/\lambda)}{\pi L_b/\lambda}\right]^2 \le \left[\frac{1}{\pi L_b/\lambda}\right]^2 = \left[\frac{1}{\pi 240/47}\right]^2 = 0.004, \qquad (9)$$

Eq. (2) and Eq. (5) give an expected 1.8μJ of undulator radiation. Again, much more radiation had occurred than was expected. This led to an investigation of the dependence of radiated energy on undulator length, in order to test for self-amplified emission, which would be expected to show exponential growth (10).

Radiated Energy at 47μm vs. Undulator Length

To measure the radiated energy as a function of undulator length, ferromagnetic plates were placed between the undulator magnets and the beam pipe. These plates reduced the magnetic field at the beam from 800 to about 30 G, shifting the resonant frequency far out of the coherent regime. To change the undulator length in this manner, the linac had to be turned off briefly to allow access. The radiated energy was measured in the Michelson interferometer M2. As periods at the downstream end of undulator were covered, the effective source point of the radiation moved upstream; the effective acceptance of M2 is estimated by Eq. (4) to account for this effect. The results are presented in Figure (7), and show an apparent exponential growth. A more detailed comparison with one dimensional self-amplified spontaneous emission theory appears elsewhere (11).

SUMMARY

In summary, coherent undulator radiation from sub-picosecond electron bunches has been observed in the 50-200μm range. The observations show

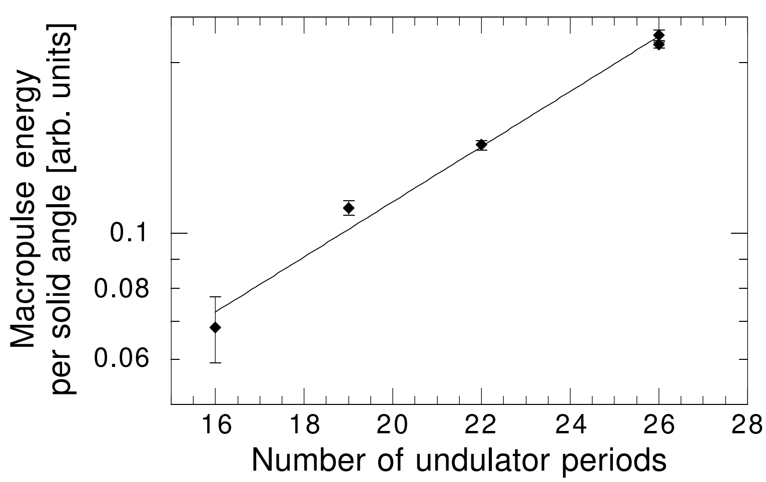

FIGURE 7. Semilog plot of measured undulator radiation as a function of undulator length. The fit line illustrates the exponential growth.

properties such as a narrower angular distribution and higher forward power than can be explained by ordinary coherent enhancement; these properties are under investigation. A measurement of forward energy at 47 μm vs. undulator length showed apparent exponential growth of the radiated energy, which is a signature of self-amplified spontaneous emission, and similiar measurements are being attempted at longer wavelengths. The interpretation of these results provides an interesting area for further research.

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