Measured free-electron laser microbunching using coherent transition radiation

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Abstract

The microbunch distribution of an electron beam exiting a SASE free-electron laser has been measured using the emitted coherent transition radiation (CTR) produced from a thin aluminum foil placed at the end of the undulator. The wavelength of the coherent transition radiation is shown to be the same as the FEL wavelength, and thus a measure of the beam microbunch spacing. Also, the study of the CTR linewidth and angular acceptance of the radiation captured are shown to be derived from this coherent radiative process. Scattering effects on the forward emitted transition radiation from the electron beam traversing an aluminum foil are also considered. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Longitudinal modulation of electron beams is now generated with many types of devices such as the free-electron laser (FEL) \cite{1}, inverse FELs \cite{2}, and plasma and structure acceleration \cite{3}. The periodic beam modulation formed from these devices is at time scales where usual diagnostic methods like streak cameras \cite{4} and RF sweeping \cite{5} cannot be used. Instead of these time-domain methods, frequency-domain measurements using coherent transition radiation (CTR) from metallic foils have shown promise in the measurement of very short electron pulses \cite{6-8}. The high-gain process of FELs is directly related to beam microbunching and gives an opportunity to use CTR to measure microbunch spacing down to several femtoseconds.

2. Theoretical background

Describing the beam distribution exiting an FEL has been done in Ref. \cite{9}, but in the present experiment, asymmetries in transverse beam dimensions were present at the exit of the wiggler and at the CTR foil and must be included. Thus, the electron
beam distribution now looks like

\[ f(r, z) = \frac{N_b}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z} \exp\left( -\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2} - \frac{z^2}{2\sigma_z^2} \right) \times \left[ 1 + \sum_{n=1}^{\infty} b_n \sin(nk_p z) \right] \] (1)

where \( N_b \) is the number of electrons, \( k_p \) is the FEL radiation wavenumber and thus the modulated micro-bunch beam wavenumber, and \( b_n \) is the bunching factor. Analysis of the CTR follows Ref. [8] where the energy spectrum is given by

\[ \frac{d^2U}{d\omega d\Omega} \approx N_b^2 F_L(\omega)F_T(\omega, \theta) \gamma(\theta) \frac{d^2U}{d\omega d\Omega}_{\text{single } e^{-}}. \] (2)

Here \( F_L(\omega) \) and \( F_T(\omega, \theta) \) are the square of the longitudinal and transverse beam profile Fourier transforms. \( \gamma(\theta) \) is a divergence factor which is usually ignored in analysis, but will be shown to be very important for forward emitted CTR. Putting Eq. (1) into Eq. (2) and integrating, the CTR photon number angular dependence is found to be

\[ \frac{dN_{\text{CTR}}}{d\theta} = \frac{\alpha(N_b b_N)^2}{4\sqrt{\pi}nk_p\sigma_z} \left( \frac{\sin^3(\theta)}{(1 - \beta \cos(\theta))^2} \right)^* \gamma(\theta) \times \exp\left[ - (nk_p \sin(\theta))^2(\sigma_x^2\sin^2(\phi) + \sigma_y^2 \cos^2(\phi)) \right] \] (3)

where \( \theta \) and \( \phi \) are the polar and azimuthal angles and \( \alpha \) is the fine structure constant. Most of the CTR light is found in a small annular cone with a maximum, using an axisymmetric beam of size \( \sigma_r \), near \( \theta \approx 1/\sqrt{2nk_p} \). Ignoring the divergence factor and integrating Eq. (2), the number of photons can be found by the straightforward relation

\[ N_{\text{CTR}} = \frac{\alpha(N_b b_N)^2}{4\sqrt{\pi}nk_p\sigma_z} \left( \frac{\gamma}{\sin(\theta)} \right)^4 \left( \frac{\sigma_x^2 + \sigma_y^2}{\sigma_x^2\sigma_y^2} \right). \] (4)

In order to best maximize the number of photons, Eq. (4) shows the electron beam must be very dense at the foil. It should also be noted that the above relation is for normal incidence of the electron beam on the foil.

3. Experimental setup

The present experiment was performed at Los Alamos National Laboratory. A 1300 MHz RF photoinjector produces a 100 bunch train of low-emittance high-current bunches. Relevant beam parameters are given in Table 1. The wiggler used is the permanent magnet 2 m Kurchatov undulator with a period of 2.01 cm and is the same one used in the high-gain SASE FEL in Ref. [10]. For the CTR experiment, a 6 \( \mu \)m foil was put on an insertable mount which when inserted was 2 cm away from the last period of the wiggler and normal to the electron beam. Also, the foil covered the entire exit aperture of the wiggler so when inserted, all the FEL radiation would be reflected back and the only light to propagate down the optical beamline would be the forward emitted CTR. The close proximity of the foil to the end of the wiggler is very important. First, there would be very little electron beam debunching [11] from space-charge effects and second, the source points and the optical beamline for the FEL (foil extracted) and CTR (foil inserted) radiation would be the same. A calibrated HgCdTe detector was installed 3.5 m away from the source point causing the angular acceptance of the optical beamline to be about 12 mrad. Mainly coherent radiation would be collected, since the incoherent spectrum is peaked at a much larger angle, \( \theta_{\text{inc}} \approx 1/\gamma \approx 30 \text{ mrad} \).

For the present experiment, the system was run at a charge of 1.5 nC and the conditions for the high-gain SASE FEL in Ref. [9] were reestablished. Once the maximum SASE signal was obtained and the foil inserted, it was found that a minor RF phase adjustment of 2° was necessary in order to maximize the CTR signal (and thus the micro-bunching of the beam) emanating from the foil. In this case, adjustments to minimize the spot size through RF focusing would enhance the CTR radiation as predicted by Eq. (4) and also negligibly change the final beam energy. Simulations using the 3-D FEL code Ginger were done for a series of experimental parameters giving a bunching factor

\( ^{1} \text{SASE FEL gain in excess of } 10^5 \text{ was first seen in this experiment.} \)
4. Results

In order to compare the measured photon number with that predicted in Eq. (4), the attenuation factor \( \chi(\theta) \) introduced in Ref. [7] must now be examined. When the radial scattering of the beam through the foil is much less than the angular spread of the incoherent radiation, \( \sigma' \approx \theta_{\text{scat}} \ll \gamma, \) the attenuation can be ignored. When this condition is violated, \( \chi(\theta) \) becomes a complicated integral and must be done numerically and quickly becomes less than unity. Defining a degradation factor, \( \eta \), it is found the forward emitted CTR signal through the 6 \( \mu \)m foil is reduced by a factor of 0.61. It should be noted that this experiment was first attempted with a 50 \( \mu \)m foil in which the CTR was greatly smaller than expected (\( \eta = 0.11 \)) leading to the examination of scattering issues in the foil. Using the predictions from Ginger and numerically integrating Eq. (2), the range of expected photons is \( N_{\gamma} = 2.8 \times 10^{8} - 4.4 \times 10^{8} \). The calibrated measured photon number per pulse from the HgCdTe detector was \( 3.5 \times 10^{8} \). To within experimental and simulation uncertainty, the numbers agree quite well.

Next the SASE and CTR signals were sent through a Jerrel Ash monochrometer. The results are shown in Fig. 1. The SASE signal is attenuated by a factor of 3 and the CTR signal is multiplied by 12 to give it the same scale as SASE and the resolution for the monochrometer was found to be 0.177 \( \mu \)m. As seen in the figure, the signals are nearly centered around the same wavelength (13 \( \mu \)m) as expected. This shows that the microbunching of the beam is at the SASE radiation wavelength agreeing with theory.

5. Conclusion

The microbunching of an electron beam due to the FEL gain process has been shown to have a spacing equivalent to that of the radiation wavelength. Also, the narrow angular spectrum and form of the spectral linewidth were measured and shown to correspond with the theoretical predictions. When doing forward scattered CTR experiments, foil thickness and scattering effects must be carefully considered. This method of diagnosing a microbunched electron beam is being planned for the Visible FEL experiment at Brookhaven National Lab in which the microbunch spacing and radiation wavelength will be near 800 nm.

References