A MEASUREMENT OF HIGH GAIN SASE FEL INDUCED ELECTRON BEAM MICRO-BUNCHING USING COHERENT TRANSITION RADIATION*

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Abstract

Coherent transition radiation (CTR) was used to study the longitudinal modulations of an electron beam exiting the UCLA/LANL high gain SASE FEL. The induced longitudinal micro-bunching of the electron beam at the exit of the undulator was measured with a frequency domain technique using the CTR emitted when this beam strikes a thin conducting foil. Formalisms for both CTR and SASE theories are related using the simulation code GINGER in which the SASE FEL gain of the output radiation and the micro-bunching of the electron beam are given. Experimental results from the CTR measurement will show the limit of standard transition radiation (TR) theory is being approached and new analysis is needed.

1 INTRODUCTION

Diagnostics measuring very short periodic electron beam modulations will be necessary for future experiments in which the modulating wavelength will be several microns and less. Up to the present, time domain measurements such as the streak camera and interfermetric CTR [1] have reliably measured the longitudinal structure of electron beams to a resolution of several hundred femtoseconds. However, as advanced accelerating techniques [2] and FELS [3,4] are becoming more common, a dependable means of measurement for these very short longitudinal electron beam modulations are needed. Using the CTR frequency domain technique described here, a higher resolution than the time domain measurements can be achieved.

A SASE FEL was used to induce the longitudinal electron beam modulation and as this beam strikes a thin conducting foil, the emitted CTR will give information about the electron beam spatial distribution. For the SASE FEL process, this electron beam micro-bunching is directly related to the gain of the SASE radiation and using CTR, we are able to reconstruct the beam distribution at the undulator exit. The results presented here agree well with the predicted performance of the SASE FEL given by simulation. Since we will be studying forward emitted CTR, scattering effects in the foil will be shown to cause a significant degradation in the emitted signal.

2 BACKGROUND

This section reviews the theory of transition radiation (TR) needed to understand the experimental measurements and also to point out the assumptions made in the standard model that may not be entirely accurate for this and future experiments.

The emitted coherent radiation energy spectrum from a multi-particle electron beam striking a metallic foil is given by

$$\frac{d^2U}{d\Omega d\omega} \approx N^2 \left| f(\omega) \right|^2 \left. \frac{d^2U}{d\Omega d\omega} \right|_{1\ e^-} \tag{1}$$

where N is the number of electrons in the bunch, Ω is the solid angle, ω is the frequency of radiation, and

$$f(\omega) = \int \exp\left(\frac{i\omega \vec{r} \cdot \hat{n}}{c}\right) S(\vec{r}) d^3r \tag{2}$$

is the Fourier transform of the beam particle distribution, $S(r)$. Immediately from Eq. 1, one sees the emitted CTR spectrum has the same Fourier spectrum as the electron beam distribution and any modulations in the electron beam will be seen in the emitted CTR spectrum.

The single electron energy spectrum for transition radiation (TR) is given by the familiar relation,

$$\left. \frac{d^2U}{d\Omega d\omega} \right|_{1\ e^-} = \frac{e^2}{4\pi^2 c} \frac{\sin^2\theta}{\left(1-\beta\cos\theta\right)^2} \ . \tag{3}$$

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Eq. 3 is derived by modeling single electron TR as a collision between the electron with its image charge at the metal/vacuum boundary and using the Lienard-Weichert fields for moving charges. In addition, the frequencies of emitted radiation is assumed much smaller than the characteristic time for the collision to take place,

$$t_{coll} << t_{rad\,per} \tag{4}$$

and the assumption that $\omega \to 0$ in the Lienard-Weichert fields is used. However, it will be shown below this assumption's limit is being approached in this and future experiments and modifications to existing standard TR modeling need to be made.

The electron beam distribution exiting a SASE FEL is given by [5,6]

$$S(\vec{r}) = \frac{\exp\left(-\frac{r^2}{2\sigma_r^2}\right)}{2\pi\sigma_r^2} \frac{\exp\left(-\frac{z^2}{2\sigma_z^2}\right)}{\sqrt{2\pi}\sigma_z} \sum_n \left[1 + b_n \cos(nk_r z)\right] \tag{5}$$

where Gaussian distributions are assumed in the radial and longitudinal dimensions (r, z) and the longitudinal micro-bunching profile superimposed on the longitudinal distribution is given by a co-sinusoidal term with the harmonic wavenumber, $k_r = 2\pi / \lambda_r$, where λ_r is the longitudinal electron beam micro-bunching wavelength equal to the fundamental SASE radiation wavelength. Higher harmonic, n, wavelengths are driven by the SASE FEL process and are included in Eq. 4, but only the fundamental harmonic $(n = 1)$ induced micro-bunching could be measured in this experiment.

Integrating Eq. 2 about the solid angle, Ω, gives a line spectrum

$$\frac{dU}{dk} = \frac{N^2 b_n^2 e^2}{4\pi} \left(\frac{\gamma}{k_r \sigma_r}\right)^4 \exp\left[-(k - nk_r)^2 \sigma_z^2\right]. \tag{6}$$

Notice, there is a peak in the emitted CTR line spectrum at the micro-bunching frequency as expected from Eq. 2. Each peak is very narrow compared to the separation with the neighboring harmonic Gaussian if $\sigma_r >> \lambda_r$. The total energy of the emitted CTR is found integrating Eq. 5 to be

$$U_{CTR} = \frac{(Nb_1 e)^2}{4\sqrt{\pi}\sigma_z} \left(\frac{\gamma}{k_r \sigma_r}\right)^4. \tag{7}$$

It can be seen from Eq. 7 that the CTR energy depends heavily on having a highly focused electron beam at the foil since $U_{CTR} \propto 1/\sigma_r^4$.

It should be noted that Eq. 6 was found integrating over the solid angle, but in the next section we will see the angular acceptance of the optical beam was only $\theta_{acc} = 15mrad$. Also, the beam must propagate through the foil to emit forward CTR (at the back surface of the foil) and degradation of signal due to scattering effects in the foil needs to be included. Both of these effects will be accounted for in the theoretical analysis of this experiment.

3 EXPERIMENTAL SETUP

The CTR/SASE experiments were performed at the Advanced FEL (AFEL) at Los Alamos National Laboratory in which the experimental setup has been described elsewhere [7], but is reviewed briefly here. Important experimental parameters are given in Table 1.

Table 1: Electron beam and SASE FEL parameters.

Beam Energy	E	17.5 MeV
Charge/bunch	Q	1.2 nC
Bunch Length (FWHM)	τ	9.2 ps
Wiggler period	λ_u	2 cm
On axis field	B_0	7.4 kG
FEL Wavelength	λ_r	13 µm
RMS beam size	σ_r	180 µm

The AFEL photo-injector uses a 10.5 cell L-band standing wave accelerator running at 1300MHz. A modelocked (108MHz) diode pumped Nd:YLF is compressed using a fiber/diffraction grating pair and then amplified with a pair of flashlamp pumped Yd:YLF rods. The emitted pulse train has 350 individual pulses separated by 9.23ns each with a FWHM of 9.2 ps. When the laser pulse train illuminates the Cs_2Te cathode, an electron train with nearly the same parameters as the laser train is created and accelerated down the beamline with each electron bunch having a charge of 1.2nC. Solenoids are placed near the cathode for emittance compensation and before the undulator to match the electron beam to the proper SASE FEL conditions.

The 2m undulator was built from a collaboration between the Kurchatov Institute and UCLA [8] and has a magnetic period $\lambda_u = 2.06cm$, on axis field $B_0 = 7.4kG$, and a normalized undulator field $K \approx 1$. An insertable $6\mu m$ radiating foil was placed 1 cm behind the last undulator period. When inserted, the foil reflects all the SASE radiation (skin depth <50 nm) and the only light to continue down the optical beamline to the calibrated HgCdTe detector is the forward emitted CTR. When the radiating foil is retracted, only the SASE radiation will propagate to the detector. Since the SASE and CTR are at the same wavelength (see Eq. 6) and have the same source points, the end of the undulator, the collecting optics need not be changed from the two measurements.

The HgCdTe detector was placed about 3.5 m from the source point which limited the angular collection of the optical beamline to just $\theta_{acc} = 15 mrad$ and Eq. 7 is not entirely correct. To correct for this, numerical integrations of Eq. 1 are done out to θ_{acc}. Also, θ_{acc} forces collection of the coherent transition radiation which is emitted at $\theta_{coh} = (\sqrt{2}\sigma_r k_r)^{-1} \approx 8 mrad$ and very little collection of the incoherent light emitted at $\theta_{incoh} \approx 1/\gamma = 28 mrad$. Included in the numerical integration is the effect of electron beam scattering within the foil. The forward emitted CTR is derived from the electron beam propagating through the foil and is emitted when the beam travels from metal to vacuum at the foil back surface. Since the scattering angle is found to be $\theta_{scatt} \approx 8 mrad$, we find the transverse size of the electron beam (σ_r) will increase and the forward emitted CTR signal is degraded (Eq. 1) by almost 40% compared to a signal assuming a foil thickness of $0\mu m$.

4 MEASUREMENTS VS. THEORY

In order to accurately predict the expected emitted CTR, it can be seen from Eq. 7 the bunching factor, b, needs to be estimated. The bunching is predicted for these conditions by the 3D FEL simulation code GINGER. For a range of parameters corresponding to experimental uncertainties, the bunching is found to be $b_1 = .017$ and an estimated gain of 10^5 was achieved as reported in References 5 and 8 for this system.

An estimation for the absolute energy of the forward emitted CTR can now be calculated. Taking into consideration foil scattering effects on the electron beam, angular acceptance, θ_{acc}, the micro-bunching amplitude above and the parameters in Table 1, an energy of 3.1 pJ is predicted at the detector by numerical integration of Eq. 1. It should be mentioned that scattering degradation and θ_{acc} each reduces the total amount of expected CTR at the detector by about 40% and not including either will cause a significant overestimation of the signal. The energy measured at the detector was 2.7 pJ, agreeing well with the predicted number given above.

Next, a Jerrell Ash monochromator was placed before the detector and line spectrum measurements were taken. Because of the high attenuation of this optic, it was found the monochromator bandwidth had to be broadened in order to pass a reasonable CTR signal to the detector and an intrinsic resolution of $.177\mu m$ is estimated for the modified monochromator setting. First, the SASE radiation was scanned with the bandwidth broadened monochromator and results of this measurement are shown in Fig.1. A centroid at $12.8\mu m$ is seen in the SASE spectrum and as mentioned before, this is the modulation wavelength of the induced electron beam longitudinal micro-bunching, λ_r. Next, the screen was inserted and the emitted CTR spectrum was scanned and the results are also shown in Fig. 1. As expected, the CTR spectrum is centered around nearly the same wavelength as the SASE spectrum and is Gaussian in shape agreeing with Eq. 6. It should be mentioned the CTR has been normalized to make it the same scale as the SASE spectrum.

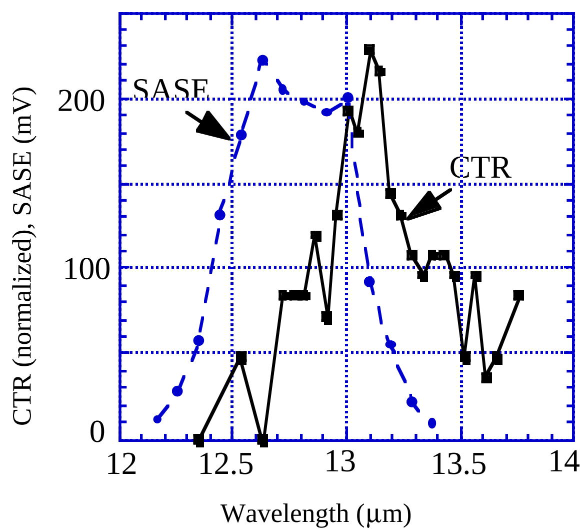

Figure 1: CTR and SASE signals as a function of wavelength with CTR scaled to SASE amplitude.

5 DISCUSSION

Because there is good agreement between the predictions and measurements presented here, the formalism developed above is assumed accurate and the electron beam distribution given by Eq. 5 is correct and no higher transverse modes are present. We have also demonstrated the narrow angular spectrum expected for coherent radiation by choosing an appropriate acceptance angle of the optical beam line to allow collection of the CTR and insignificant collection of incoherent TR. These conditions imply the electron beam micro-bunching is uniform transversely across the beam.

A slight frequency shift was observed in the CTR spectrum center shown in Fig. 1. Looking at the transition radiation model traditionally used, limits of its validity here are suspect. The criterion for using Eq. 3 for the TR spectrum is given by Eq. 4. We see in this experiment the period of emitted radiation is $t = 4.3 * 10^{-14} s$ and the assumption that this is much greater than a collision time (for the electron/image charge collision model) is questionable. If the condition in Eq. 4 is not applicable for the TR collision model, the more general spectrum for TR from the Lienard-Wiechert fields is found to be

$$\frac{d^2U}{d\Omega d\omega} = \frac{e^2\omega^2}{4\pi^2 c}\left|\int_{-\infty}^{\infty} \hat{n}\times(\hat{n}\times\vec{\beta})\exp\left[i\omega\left(t-\frac{\hat{n}\cdot\vec{r}(t)}{c}\right)\right]dt\right| \tag{8}$$

where $\hat{n}$ is the unit vector from the interaction to the observation point, β is the velocity of the electron or image charge and $\vec{r}(t)$ is the trajectory of the particles in the collision. Not only do the initial velocities need to be known, but the physics of the particle trajectories during the collision must be calculated. It is immediately seen the spectrum in Eq. 8 contains additional phase information not present in the standard TR spectrum given by Eq. 3 and could account for the observed frequency shift of the CTR spectrum shown in Fig. 1. As the frequencies of emitted TR increase for future experiments, the traditional spectrum from Eq. 3 will have to be replaced by the more general TR spectrum given by Eq. 8.

6 CONCLUSION

The experiment and technique described here was shown to reliably measure longitudinal beam modulations to a few microns and less. Since this experiment was performed on a SASE FEL, this measurement verified the crucial role of micro-bunching in the SASE FEL gain process. Simulations were used and the results agreed well with the measurements described above, thus serving as an independent check on the code predictions.

7 REFERENCES

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