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OBSERVATION AND CHARACTERIZATION OF COHERENT OPTICAL RADIATION AND MICROBUNCHING INSTABILITY IN THE SLAC NEXT LINEAR COLLIDER TEST ACCELERATOR*

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Abstract

The NLC Test Accelerator (NLCTA) at SLAC is currently configured for a proof-of-principle echo-enabled harmonic generation (EEHG) experiment using an 120 MeV beam. During commissioning, unexpected coherent optical undulator radiation (CUR) and coherent optical transition radiation (COTR) was observed when beam is accelerated off-crest and compressed after the chicanes. The CUR and COTR is likely due to a microbunching instability where the initial small ripples in cathode drive laser is compressed and amplified. In this paper we present the observation and characterization of the CUR, COTR and microbunching instability at NLCTA.

INTRODUCTION

Magnetic bunch compressors are generally used to provide high peak current beam to drive the FELs. However, in the bunch compression process the initial current modulations (from drive laser ripples, shot noise, etc) may be amplified and a microbunching instability may develop which can degrade the beam quality and the FEL performance [1, 2, 3]. The process is similar to a high gain klystron-like amplifier where the initial density modulations cause energy modulations due to impedances; the energy modulations are then converted into density modulations in the bunch compression through a dispersion section; after beam's passage through the chicane, the initial density modulations are amplified and finally the microbunching instability develops [4].

The NLC Test Accelerator (NLCTA) at SLAC is currently configured for a proof-of-principle echo-enabled harmonic generation (EEHG) experiment [5] using an 120 MeV beam. The beam line includes a photocathode rf gun, two X-band rf structure, three undulators and four chicanes. Optical transition radiation (OTR) is used to image the transverse distribution for both the electron beam and seed lasers. During commissioning activities an enhanced CUR and COTR intensity was observed after the beam traversed a chicane with an applied energy chirp. Similar to the observations in LCLS [6], this coherent radiation is characterized by considerable shot to shot variation in transverse profile, intensity and spectrum.

Compared to on crest, the applied chirp combined with the chicane R_{56} leads to a maximal compression in bunch length by a factor of about 20 for which case the final bunch length is about 30 fs. Since the minimal bunch length in the experiment is still much longer than optical wavelength, the COTR is attributed to a microbunching instability which is likely to be driven by the ripples in cathode laser.

Detailed measurements show that the COTR intensity correlates with bunch length and the maximal COTR intensity is obtained at full compression. In this paper the observation and characterization of the COTR and microbunching instability at NLCTA is presented.

OBSERVATION OF COHERENT OPTICAL RADIATION

The NLCTA echo beam line is schematically shown in Fig. 1. It consists of an S-band photo-cathode RF gun, two X-band accelerator sections (X1, X2), three undulators (U1, U2 and U3) and four chicanes (C-1, C0, C1, and C2). The details of the beam line can be found in [5].

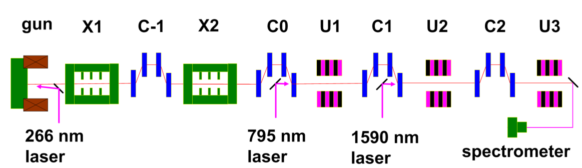

Figure 1: NLCTA echo beam line layout.

Table 1 lists the typical operating parameters for the NLCTA facility.

Table 1: Machine parameters

parameter	ECHO
Beam energy	120 MeV
Bunch length	150-600 um
Normalized emittance	8 mm-mrad
Bunch charge	20-40 pC
Slice energy spread	1 keV

Our first observation of coherent optical radiation was made during commissioning under conditions of no laser interaction. The coherent optical radiation was observed at the OTR screen just downstream of U1. Because the radiation generated in U1 is also reflected out by the OTR

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screen, the measured signal consists of both undulator radiation and OTR. In the experiment, the momentum compaction of C0 is set to $R_{56} = 5.5$ mm. The measured radiation distribution for various rf phases in X2 is shown in Fig. 2.

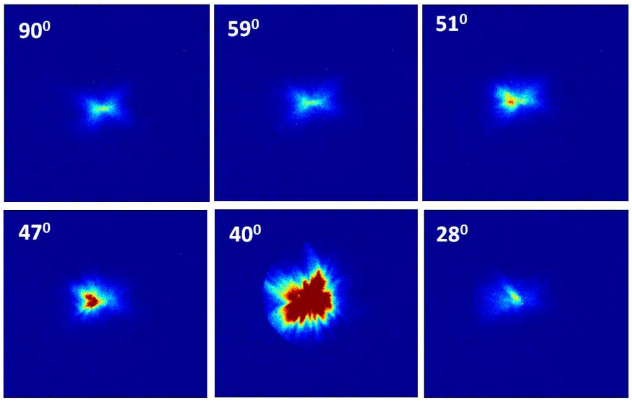

Figure 2: Radiation distribution for various rf phase in X2 measured with an OTR screen downstream of undulator U1.

When the beam is accelerated on crest in X2, the measured distribution is dominated by incoherent undulator radiation where in the top-left picture of Fig. 2 one can clearly see the 4 lobes which are from the vertical component of the undulator radiation. When the beam is accelerated off crest, the energy chirp together with the chicane C0 make the beam compressed and we start to see some enhancement in the radiation intensity. For this set up, the maximal radiation intensity is achieved at an rf phase of about 40 degrees. The coherent radiation intensity is enhanced by a factor of 50 compared to the on crest case.

In another measurement we changed the momentum compaction of C0 to $R_{56} = 8.1$ mm and the measured radiation intensity for various rf phases is shown in Fig. 3. For the $R_{56} = 8.1$ mm case we found that the phase that provides maximal coherent radiation intensity shifts to about 47 degrees. Since the required energy chirp for a given compression factor is smaller for a larger R_{56}, it is likely that the coherent radiation intensity is correlated with the compression factor.

We then simulated the bunch length at the OTR screen for various rf phases in X2. As shown in Fig. 4, the phase that provides maximal compression shifts by about 7 degrees when chicane momentum compaction is increased to $R_{56} = 8.1$ mm. A comparison between Fig. 3 and Fig. 4 clearly indicates that the maximum radiation intensity is achieved at the minimum bunch length.

Given the initial bunch length of about 0.6 ps, simulation shows that the shortest bunch length at the OTR screen is about 30 fs. It is still too long to generate coherent radiation in optical wavelength. It is likely that the initial ripples in the cathode laser with a density modulation of $\sim 20\ \mu$m was compressed and amplified through microbunching instability [2, 3] to generate coherent optical radiation.

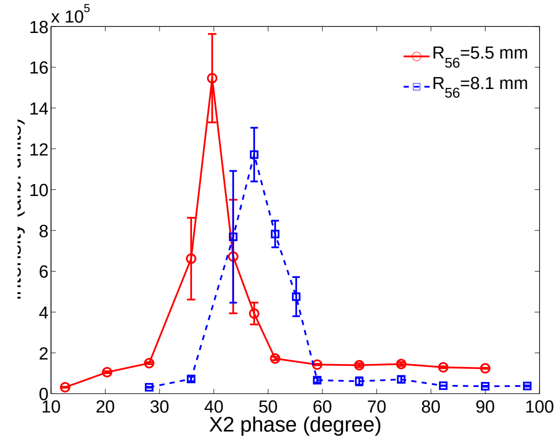

Figure 3: Measured coherent radiation intensity for various rf phase in X2

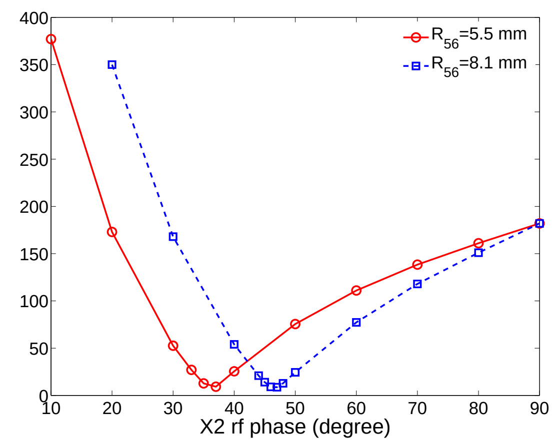

Figure 4: Simulated bunch length for various rf phase in X2. Beam is accelerated on crest at 90 degrees.

It is worth pointing out that increasing chicane R_{56} also reduced the maximal coherent radiation intensity, as can be seen in Fig. 3. This might indicate a reduction of the microbunching gain. Since the gain of microbunching instability is roughly proportional to $CR_{56}\exp(-\frac{1}{2}C^2k^2R_{56}^2\delta^2)$, where C is the compression factor, k is the initial modulation wave number and δ is the slice energy spread, increasing R_{56} may make the Landau damping from the slice energy spread more effective. Currently the NLCTA facility is under upgrade [7] and in the near future we will have the capability to vary the beam slice energy spread. We plan to have more systematic study in the future to quantify the microbunching gain for various wavelength, beam slice energy spread and chicane momentum compaction.

OBSERVATION OF COTR

To separate the CUR from COTR, we repeated the measurement with an OTR screen upstream of the undulator U3 where only the OTR will be detected by the CCD. Typical beam image of the radiation measured with the presence of COTR is shown in Fig. 5. Instead of a regular Gaussian shape, a donut-like distribution was observed. This is consistent with the theoretical prediction that when electron beam is transversely coherent, the OTR image of the beam will show the gradient of the transverse distribution which is a donut for Gaussian distribution [6].

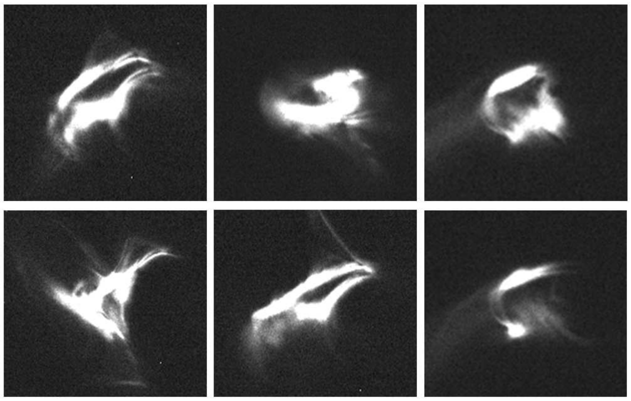

Figure 5: Typical COTR near field images for different shots.

A 300 lines/mm grating is further used to resolve the spectrum of the COTR signal. The incoherent OTR spectrum was first measured and shown in the top picture of Fig. 6 where one can see a flat spectrum in the optical wavelength. The radiation at zero wavelength is actually the zeroth order radiation that transmits through the grating.

When beam is accelerated off crest to generate COTR, the typical spectra show enhancement at some discrete wavelength. The presence of spectral lines is a strong indication that the beam temporal profile has fine structures at the optical wavelength.

SUMMARY

Microbunching instability is one of the most challenging threats to FEL performance. The NLCTA echo beam line has four chicanes, so the microbunching gain can be potentially high. During the commissioning of the EEHG experiment, unexpected CUR and COTR was observed when beam is accelerated off-crest and compressed after the chicanes. The CUR and COTR is attributed to a microbunching instability driven by the initial small ripples in cathode laser and the bunch compression process. While this coherent radiation is characterized by considerable shot to shot variation in transverse profile, intensity and spectrum, in general its intensity correlates with the compression factor. After NLCTA upgrade we plan to have more systematic studies on COTR and microbunching instability in the near future.

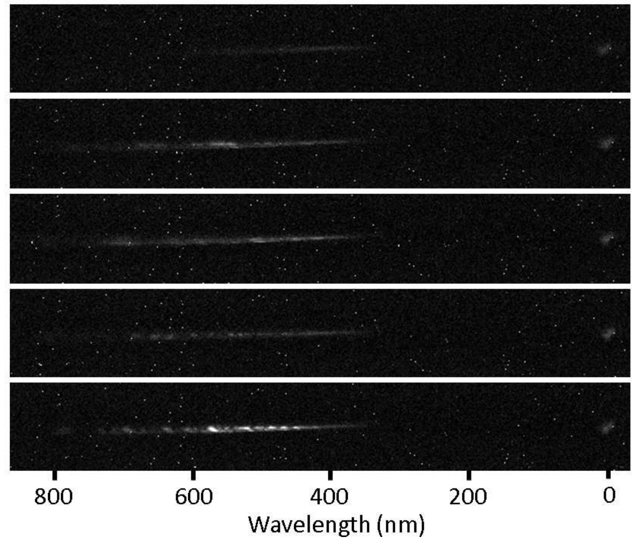

Figure 6: Typical COTR spectra for different shots. The top picture is the incoherent OTR spectrum.

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