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EXPERIMENTAL STUDY OF COHERENT THz SOURCES DRIVEN BY THE NSRRC HIGH BRIGHTNESS PHOTO-INJECTOR

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Abstract

Accelerator-based coherent THz radiation sources are being studied with the NSRRC high brightness photo-injector which has been installed in the Accelerator Test Area (ATA) recently. This injector is equipped with a laser-driven photocathode rf gun and a 5.2-m long S-band traveling-wave linac for beam acceleration. A few tens MeV, ultrashort bunches of ~100 fs bunch length can be produced from the injector by velocity bunching technique. Tunable narrow-band THz coherent undulator radiation can be generated from a U100 planar undulator when it is driven by such beam. In addition, broadband THz coherent transition radiation generated by passing this beam through a metallic foil is used for determination of bunch length by autocorrelation technique. The laser-driven photo-injector, the THz experimental setup and results are presented in this paper.

INTRODUCTION

Terahertz (THz) radiation has recently attracted a lot of attention in scientific applications, such as spectroscopy, imaging, communications and elementary excitations. Over the past decade, fruitful development of laser-based THz sources as well as nonlinear optics leads to a partial fill up of the THz-gap. Accelerator-based THz radiation sources attract much attention in recent years [1, 2]. It is well-known that a relativistic electron beam emits temporal coherent synchrotron radiation when its bunch length is much shorter than the radiation wavelength [3]. Realization of a fully coherent THz light is possible if an ultrashort and simultaneously a low-emittance electron beam is available. For modern photo-injector, the beam transverse emittance is usually much smaller than that of the photon beam and therefore, radiation with excellent spatial coherence can be achieved. A high brightness photo-injector has been developed at NSRRC a few years ago. In this report generation of coherent THz sources from CTR and CUR with this photo-injector is reported.

ACCELERATOR-BASED COHERENT THz SOURCES

Accelerator-based coherent radiation can be generated when the radiation wavelength is longer than the bunch length. Once the bunch length can be compressed to few hundred or few tens fs, coherent radiations in the THz range can be produced. In general, the radiation power from an electron bunch with N electrons can be described as $P(\omega) = P_0(\omega)\left[N\left(1 - f(\omega)\right) + N^2 f(\omega)\right]$, where $P_0(\omega)$ is the radiation power of single electron and $f(\omega) = \left|\int e^{ik\hat{n}\cdot\vec{r}} S(\vec{r}) d^3r\right|^2$ is the bunch form factor which is the Fourier transform of the temporal distribution of the electrons in the bunch. $S(\vec{r})$ is the 3D particle distribution. In the square bracket of the equation, the first term is incoherent component and the second is the coherent one, which is related to the square of the electron number and the bunch form factor. The power of coherent radiation will be about N^2 times larger than that of one electron.

There are several mechanisms to produce coherent radiation in accelerator-based sources. One of them is coherent transition radiation (CTR) [4]. Transition radiation (TR) is emitted when a charged particle passes through the boundary of two media with different dielectric constant. When the bunch length is much smaller than the radiation wavelength, the CTR is produced. The CTR carries the information of the bunch distribution. Therefore the CTR can be measured with an interferometer to obtain the autocorrelation trace of the bunch electric field, and then the bunch length can be deduced from the autocorrelation measurement. Another way to produce coherent THz radiation is undulator radiation. Just like the coherent synchrotron radiation from bending magnets, undulators can be used to produce synchrotron radiation with significantly higher brightness at narrow spectral bandwidth, so called coherent undulator radiation (CUR). The radiation wavelength of CUR can be determined by $\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$, where λ_u is the undulator period length, K is undulator parameter, γ is the Lorentz factor and θ is the observation angle from the beam.

ULTRASHORT ELECTRON BUNCHES VIA VELOCITY BUNCHING

The concept of rf compression in photo-injector by velocity bunching was first suggested in 2001 [5]. This method is a one-step scheme that beam acceleration and compression are accomplished simultaneously in the accelerating structure. Propagation of microwave in a typical traveling wave linac has a constant phase velocity equal to the speed of light. An electron moving slower than the phase velocity slips in phase with respect to the rf wave until it is accelerated to higher energy. In general the amount of electron phase slippage depends on the injection phase. Therefore, it is possible that a bunch of electrons with different initial phases being injected into the linac at certain nominal rf phase will slip backward to the crest of the accelerating field such that bunch compression can be achieved. Velocity bunching is attractive because less space is required in comparison with the magnetic bunching scheme. However, it should be noted that velocity bunching is effective only for lower

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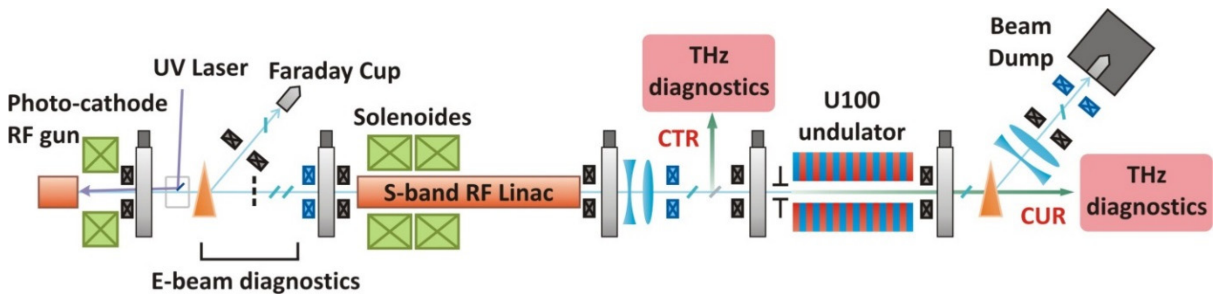

Figure 1: Layout of the NSRRC high brightness photo-injector and coherent THz sources.

energy electron beams and the transverse beam emittance and beam size has to be controlled carefully.

NSRRC HIGH BRIGHTNESS PHOTO-INJECTOR

The commissioning of the high brightness photo-injector, aimed to develop a 100 MeV photo-injector system for light source R&D, has been carried out in 2016 [6]. The layout of the photo-injector is shown in Fig. 1. The photo-injector is composed of a Cu photocathode gun, operating at 2998 MHz with peak accelerating gradient of 70 MV/m. The gun is followed by a solenoid which is used to compensate space charge induced emittance growth. A Ti:sapphire laser system, delivering 800 nm, 100 fs pulses with energy of 3.5 mJ, is used as a drive laser system to produce the 266 nm UV light required for the photocathode through a third harmonic generation unit. A synchrolock system will make sure that the laser is synchronized with the 40th subharmonic (74.95 MHz) of the master clock at 2.998 GHz. A 5.2-m-long, 156-cell, DESY-type constant gradient traveling wave linac is used as rf compressor. Two solenoid coil sets embedding this linac provide additional magnetic focusing to control the beam envelope and reduce the emittance growth under velocity bunching. Both the gun and the linac are powered by one 35 MW klystron. A tunable power splitter and phase shifter will allow us to tune the power and the phase independently. Diagnostic beam line is installed at downstream of the linac to characterize the electron beam. Charge and current are measured using the integrating current transformers (ICT). Beam energy is measured using the dipole magnet spectrometer, and the beam position is measured at various positions along the beam line with YAG:Ce screen imaging systems.

THz SETUP AND MEASUREMENT

The setup of CTR and CUR and the THz diagnostics station for THz measurements, shown in Fig. 2, are described as follows.

Coherent Transition Radiation

A 20-mm diameter Al foil with 45° with respect to the beam path was used as a CTR radiator. The backward TR is emitted perpendicular to the beam axis and then collected and collimated by a gold-coating 90º off-axis parabolic mirror (OAP) with 9-inch focal length through a THz Tsurupica window (Broadband Inc.), which is made of transparent material and has the same refractive index at both THz light and visible wavelength. Then the CTR is further transported to the THz diagnostics station by another gold-coating mirror. The Al foil and the YAG screen are mounted on the same motorized linear motion feedthrough. By moving the motion feedthrough to different positions, which means the YAG screen or the Al foil is moved to the beam axis, the beam status and the CTR signal can be observed.

Coherent Undulator Radiation

The planar undulator U100 with an 18 periods, 10 cm period length and physical length 2.2 m, which was designed and fabricated by NSRRC, is used to generate the coherent THz radiation. It was installed at 1.52 m downstream from the linac exit. The undulator gap can be varied from 24 mm to 120 mm. The maximum peak B field is 0.945 T which corresponds to K value of 8.8 when the gap is set at the minimum value of 24 mm. The gap is fixed at 40 mm, corresponding to undulator constant K of 4.6, for the CUR experiments. The ultrashort electron beam from the photo-injector and the THz photon beam coexist in the undulator vacuum chamber. While the THz radiation goes straight ahead to the THz output window, a dipole magnet bends the electron beam to the dump. Another THz Tsurupica window is used at the end of the

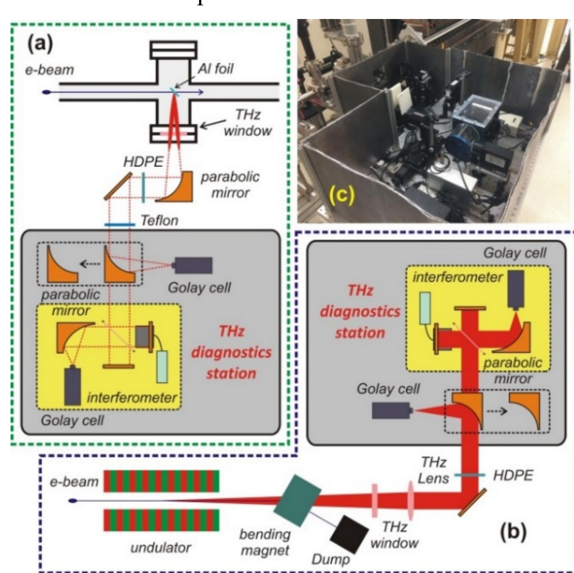

Figure 2: Schematic of the setup of THz measurement for (a) CTR, (b) CUR and THz diagnostics station with the photo shown in (c).

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entire vacuum chamber. Different from CTR, a THz Tsurupica lens (Broadband Inc.) with 2.5-m focal length is used to collect and collimate the THz radiation and three gold mirrors are used to transport the THz radiation to the THz diagnostics station.

THz Diagnostics Station

A THz diagnostics station is built for characterizing the THz signal. Once the collimated THz radiation is transported into the station, an OAP with 15-cm focal length which is mounted on a translation stage is used to focus the signal onto the THz detector and then the THz power can be measured. The THz detector is a Golay cell detector (Tydex, GC-1P). HDPE and Teflon plates are inserted in front of the OAP to filter out the unwanted light and attenuate the THz power to avoid detector saturation. Once the OAP is moved away, the THz radiation can be directed into a bunch length interferometer system, which is an in-air Michelson interferometer setup for power spectrum measurement. The interferogram of the recombined signal coming from two optical arms is detected by another Golay cell detector. The THz diagnostic station is purged with dry air to prevent the propagation loss of THz radiation in air and covered by Pd sheet for radiation shielding.

EXPERIMETAL RESULTS

Currently a 2.8 MeV electron beam with bunch charge up to 460 pC is generated from the photocathode gun operated at the rf accelerating gradient of 11.5 MV/m while the electron beam is accelerated to the energy of 62 MeV through the linac. The injection phase of the electron beam is tuned for bunch compression until the CTR signal reaches maximum and then the injection phase is fixed for all measurements. Figure 3 shows the measurement of the THz intensity as a function of electron number for CUR and CTR. The results confirm the quadratic dependence of the THz output signal on the electron number as expected both for CTR and CUR. Measured interferograms by the Michelson interferometer for CUR (red line) and CTR (blue line) sources are shown in Fig. 4(a). As mentioned earlier, the electron bunch length can be determined from the measured CTR interferogram. As shown in inset of Fig. 4(a), the measured FWHM for the bunch is 346 μm. Assume the electron bunch is Gaussian distribution, the bunch length is estimated to be 490 fs rms. The measured bunch length

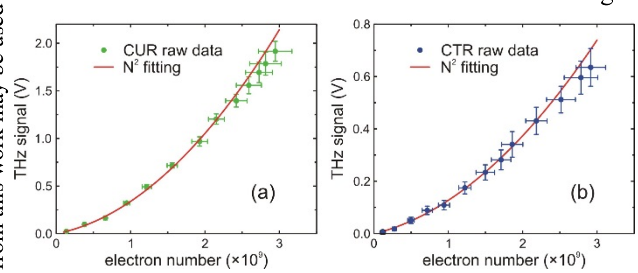

Figure 3: THz output signal as a function of the electron number for (a) CUR and (b) CTR.

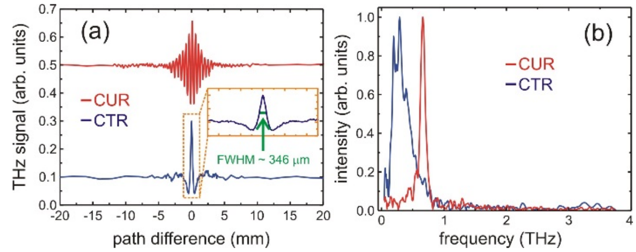

Figure 4: (a) Measured interferograms for CUR (red line) and CTR (blue line) sources. The inset shows the enlargement of the central part of CTR signal. (b) THz spectra retrieved from the interferograms in (a).

is longer than the calculated results of sub-hundred fs. This may cause by the lower linac field of 11.5 MV/m whereas the field for calculation is 15 MV/m. The radiation spectra for CUR and CTR retrieved from interferograms in Fig. 4(a) by fast Fourier transform are shown in Fig. 4(b). In contrast, the CUR spectrum is narrow band and the central frequency is measured to be 0.62 THz, corresponding to the electron beam energy of 17.7 MeV. Exclude the energy loss caused by the response of the Golay cell detector, transmittance of HDPE and Teflon plates, and throughput of all optics, the estimated THz pulse energies for CTR and CUR are 6.7 and 26.4 μJ under the electron charge of 210 and 280 pC, respectively. Performance of the coherent THz sources for CTR and CUR are summarized in Table 1.

Table 1: Performance of Coherent THz Sources

Parameters	CUR	CTR
Beam energy (MeV)	17.7	
Bunch charge (pC)	280	210
Bunch length (fs)	490	
Repetition rate (Hz)	10	
Undulator strength K	4.6	--
THz pulse energy (μJ)	26.4	6.7
Central frequency (THz)	0.62	--
Bandwidth	15%	--
THz peak power	530 kW	9.4 MW

SUMMARY

Accelerator-based coherent THz sources have been studied to demonstrate the capability of the NSRRC high brightness photo-injector. Narrow-band THz CUR can be generated from a U100 planar undulator. Considered the power loss of the THz optics, the radiation pulse energy at the exit of the undulator chamber is 26.4 μJ under the electron charge of 280 pC. From the CTR and autocorrelation technique, currently the electron bunch length is measured to be 490 fs due to insufficient linac field. The results show that electron bunches in the linac can be accelerated and compressed simultaneously by velocity bunching. Improvement of better beam quality and higher repetition rate of this photo-injector is under consideration.

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REFERENCES

[1] N. Stojanovic and M. Drescher, "Accelerator and laser-based sources of high-field terahertz pulses", *J. Phys. B: At. Mol. Opt. Phys*., no. 46, 192001, 2013.

[2] S. Benson *et al.*, "The 4th generation light source at Jefferson Lab", *Nucl. Instrum. Methods A*, vol. 582, 14, 2007.

[3] T. Nakazato *et al.*, "Observation of coherent synchrotron radiation", *Phys. Rev. Lett.,* no. 63, 2433, 1989.

[4] C. Settakorn, "Generation and use of coherent transition radiation from short electron bunches", Ph.D. Thesis, Stanford University, California, 2001.

[5] L. Serafini and M. Ferrario, "Velocity bunching in photo-injectors", *in Proc. Physics of, and Science with, the X-ray Free Electron Laser,* Arcidosso, Italy, 2001, No. 581, pp. 87-106.

[6] A. P. Lee *et al.*, "First beam test of the high brightness photo-injector at NSRRC", *in Proc. IPAC'16*, Busan, Korea, May 2016, paper TUPOW025, pp. 1800-1802.