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FIRST OBSERVATION OF COHERENT THZ UNDULATOR RADIATION DRIVEN BY NSRRC HIGH BRIGHTNESS PHOTO-INJECTOR

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Abstract

Generation and characterization of coherent undulator radiation (CUR) in the THz region using the NSRRC S-band photo-injector linac system is achieved. The system consists of a laser-driven photocathode rf gun and one 5.2-m long S-band accelerating linac. Electron bunches in the linac can be accelerated and compressed simultaneously by velocity bunching. In this work, narrow-band tunable fully-coherent THz radiation can be produced from a U100 planar undulator when it is driven by a 100-pC electron bunch with effective bunch length of 90 fs. The experimental setup and the measurement of the power and the frequency spectrum of the coherent THz undulator radiation are reported.

INTRODUCTION

Terahertz (THz) radiation has recently attracted a lot of attention in the scientific applications, such as spectroscopy, imaging, communications and elementary excitations (e. g. excitation of phonons in solids). The THz frequency which is defined as 0.1 to 10 THz (wavelengths of 3 mm to 30 μm) covers the gap between microwaves and infrared light. Development of THz technologies is hindered by the so-called “THz-gap” which reflects the lack of THz sources in the electromagnetic wave spectrum. Over the past decade, the 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]. For example, recalled that the wavelength of a 1 THz wave is 300 μm, a 100-fsec electron bunch can be used to generate coherent radiation in the THz regime such that the radiation intensity is proportional to the square of electron number in the bunch. 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 equipped with a laser-driven photocathode rf gun and a 2998-MHz, 5.2-m-long traveling-wave rf linac has been developed at NSRRC several years ago. In this report design of tunable narrow-band THz coherent undulator radiation (CUR) with this photoinjector and a 10-cm period length planar permanent magnet undulator (U100) has been studied. In addition, first observation of the THz CUR driven by this machine is also reported.

COHERENT UNDULATOR RADITION

It is well known that relativistic electrons moving in a magnetic field emit synchrotron radiation as they are accelerated by the magnetic force which is always perpendicular to the electron orbits. Undulators can be used to produce synchrotron radiation with significantly higher brightness at narrow spectral bandwidth. Coherent synchrotron radiations (CSR) from bending magnets and undulators are possible as long as the bunch length is much shorter than the radiation wavelengths. When the electron beam emittance is smaller than the radiation photon emittance, a spatially coherent beam or diffraction limited radiation can be produced. Furthermore, a temporal coherent radiation can be achieved when the radiation fields from electrons that are randomly distributed in the bunch of length σ_t add up constructively when $c\sigma_t \leq \lambda$.

In general, the radiation spectrum of the electron bunch can be described as

$$\left.\frac{d^2W}{d\Omega d\omega}\right|_{\text{multi}} = \{N[1-F(\omega)] + N^2F(\omega)\}\left.\frac{d^2W}{d\Omega d\omega}\right|_{\text{single}},$$

where N is the number of electrons in the bunch and $F(\omega)$ is the form factor which is the Fourier transform of

Table 1: Predicted Performance of THz CUR from U100

CUR from U100		
Electron charge	100 pC	100 pC
E-beam energy (MeV)	18.3 – 33.5	33.5
bunch length (fs, rms)	90 – 223	90
Undulator strength *K*	4.6	3.2 – 4.6
THz frequency (THz)	0.67 – 2.2	2.2 – 4.3
Bandwidth	5.6%	5.6%
THz pulse energy (μJ)	0.5 – 2.7	0.1 – 2.7
Repetition rate (Hz)	10	10
Average power (μW)	5 – 27	1 – 27
Peak power (MW)	0.02 – 0.32	0.02 – 0.32

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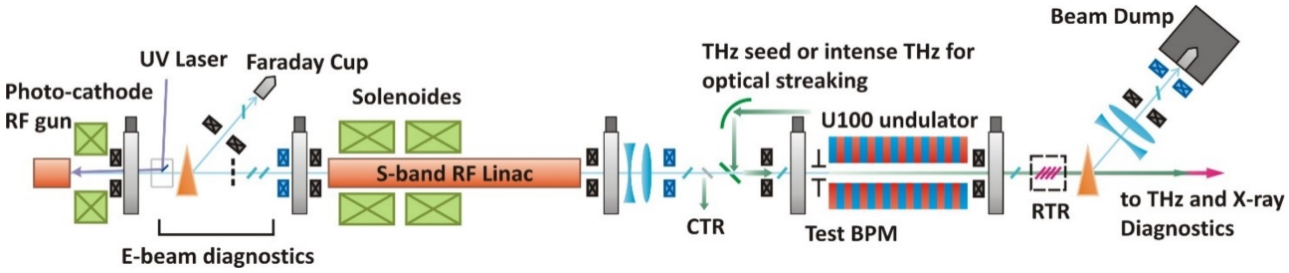

Figure 1: Layout of the NSRRC high brightness photo-injector and THz CUR source.

the temporal distribution of the electrons in the bunch. In comparison with the case of a single electron, the coherent undulator radiation of N electrons is enhanced by a factor of N^2 but the spectrum is enveloped by the form factor. Narrow-band coherent THz radiation with frequency adjustable from 0.7 to 4.0 THz can be generated from the U100 undulator (18-period undulator of 10-cm period length) when it is driven by the ultrashort electron beam. Performance of the radiation is calculated and listed in Table 1, which the transmission loss in the undulator chamber has been included in the calculation.

GENERATION OF ULTRASHORT ELECTRON BUNCHES

Magnetic bunch compressors are commonly used to enhance beam brightness in many advanced accelerator facilities. The concept of rf compression in photo-injector by velocity bunching was first suggested by Serafini and Ferrario in 2001 [4]. This alternative method is a one-step scheme that beam acceleration and rectilinear 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. Since no dipole magnets are used, deterioration of beam emittance due to CSR effect can be avoided. However, it should be noted that velocity bunching is effective only for lower energy electron beams (< 10 MeV) and the transverse beam emittance and beam size has to be controlled carefully.

With GPT simulation, a 3 ps, 100 pC electron beam generated from the laser-driven photo-cathode rf gun is injected into the rf linac at 15 MV/m accelerating field gradient for velocity bunching. A compressed beam with energy of ~33.6 MeV, bunch length of ~65 fs can be obtained at the linac exit. However, it is found that there is a moderate growth in beam size as well as a slight degradation of transverse beam emittance during the acceleration/compression process. This can be fixed by introducing solenoid magnetic field to the frontier section of the linac. The transverse growth of beam size for accelerated beam can be limited with the assistance this solenoid magnetic field.

PHOTO-INJECTOR AND THz CUR SYSTEM

High Brightness Photo-Injector

The commissioning of the high brightness photo-injector, aims to develop a 100 MeV photo-injector system for light source R&D, has been carried out at the beginning of April in 2016 [5]. The layout of the photo-injector is shown in Fig. 1.

The photo-injector is composed by a BNL/UCLA/SLAC type gun, operating at 2998 MHz with peak accelerating gradient of 70 MV/m on the cupper photocathode. The gun is followed by a solenoid which is used to compensate space charge induced emittance growth. A commercial 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 pulse stretcher capable of adjustable range of 0.8 – 14 ps is used to stretch the UV laser pulses. A synchrolock system ensures that the laser is synchronized with the 40th subharmonic (74.95 MHz) of the master clock at 2.998 GHz. A 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.

A diagnostic beam line is installed at downstream of the linac to characterize the electron beam. Charge and current are measured using 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 using YAG:Ce screen imaging systems.

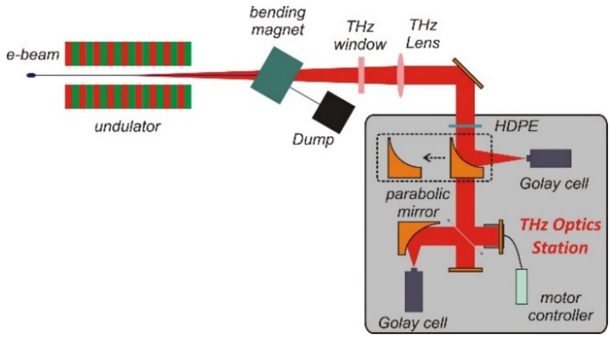

Figure 2: Schematic of the THz CUR source and the optical system for measurement.

NSRRC U100 Undulator

The planar undulator U100 with 18 periods, 10 cm period length and physical length 2.2-m was designed and fabricated by NSRRC. It was installed after the photon-injector system for the generation of THz radiation. The undulator gap can be varied from 24 mm to 120 mm. The maximum peak B field is 0.945 T which corresponds to a K value of 8.8 when the gap is set at the minimum value of 24 mm.

Coherent THz Undulator Radiation Source

Figure 2 shows a schematic of the THz CUR source and the optical system for measuring the THz output signals. 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. A THz Tsurupica window (Broadband Inc.) is used to separate the optical system which is installed in the atmospheric environment from the vacuum. A THz diagnostic system for characterizing the CUR has been installed at downstream of the dipole magnet.

The system includes: (1) a THz Tsurupica lens (Broadband Inc.) with 2.5-m focal length is used to collimate the THz radiation into a parallel beam, (2) three mirrors coated with gold are used to transport the THz radiation, (3) an off-axis parabolic mirror (OAP) with 15-cm focal length which is mounted on a translation stage is used to focus the signal onto the THz detector and (4) the THz detector is a Golay cell detector (Tydex, GC-1P) with the responsivity of 86.7 kV/W at 10 Hz modulation rate. An HDPE plate is inserted in front of the OAP to filter out the unwanted light.

Once the OAP is moved away, the THz radiation can be directed into a bunch length interferometer system. The interferogram of the recombined signal coming from two optical arms can be detected by another Golay cell detector. The bunch length and the frequency spectrum of THz radiations can be derived by analysing the interferograms. The THz diagnostic system including the THz optics and the interferometer is purged with dry air to prevent the propagation loss of THz radiation in air.

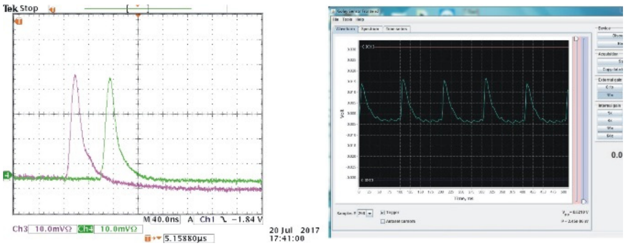

Figure 3: Left: ICT signals, the purple curve is at the linac entrance and the green one is at the linac exit; Right: the measured CUR THz signal.

EXPERIMENTAL RESULTS

A 3.5-MeV electron beam with bunch charge of 100 pC is generated from the photocathode rf gun operated at the peak rf accelerating gradient of 70 MV/m while the laser injection phase is 23° respect to the rf field. Then the electron beam is accelerated to the energy of 43.7 MeV through the linac. The bunch charge measured by the ICTs at the linac entrance and exit is almost the same as shown in the left part of Fig. 3. After that, the electron beam passed through the U100 undulator, installed at 1.52-m downstream from the linac exit, with a gap of 40 mm, corresponding to undulator constant K of 4.6, to produce the THz CUR.

The THz CUR signal was measured by the Golay cell detector, as shown in the right part of Fig. 3. Excluding the energy loss caused by the response of the Golay cell detector, HDPE transmittance, and throughput of all optics, the approximate THz pulse energy is 38.7 nJ at the exit of the undulator vacuum chamber. Parameters of the THz CUR experiment are summarized in Table 2.

In our experiment, the time jitter between the drive laser and microwave and the phase jitter of the microwave result in shot-to-shot fluctuations of bunch charge and the beam energy. Since we did not optimize the operating condition of the photo-injector, the energy of THz radiation is much lower than the predicted value. Besides, the inner height of the undulator vacuum chamber is 28 mm, different from the design value of 36 mm. We believe that the THz output power is strongly limited by the smaller chamber height. The optimization of the status of the photo-injector will be the next step to get higher THz CUR pulse energy.

Table 2: Parameters of the THz CUR experiment

Electron beam energy	43.7 MeV
Bunch charge	90 ± 10 pC
Bunch repetition rate	10 Hz
Undulator period	100 mm
Number of undulator period	18
Undulator gap	40 mm
Undulator constant, K	4.6
Inner height of undulator vacuum chamber	28 mm
THz pulse energy	38.7 nJ @ undulator chamber exit

CONCLUSION

A laser-driven photo-injector system has been developed at NSRRC for R&D of future light sources such as free electron lasers, inverse Compton sources etc. A THz CUR source (or THz superradiant FEL) has been installed to demonstrate the capability of this injector. First THz light has been observed with the Golay cell detector installed at downstream of the U100 undulator. Considered the power loss of the THz optics, the radiation pulse energy at the exit of the undulator chamber is 38.7 nJ (interception of THz energy by the undulator vacuum chamber has not been taken into account yet). Optimization of bunch form factor by velocity bunching for higher THz pulse energy and measurement of spectral distribution are in progress. Improvement of the photo-injector for lower emittance and higher repetition-rate is under consideration.

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