Tailored Terahertz Pulses from a Laser-Modulated Electron Beam

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We present a new method to generate steady and tunable, coherent, broadband terahertz radiation from a relativistic electron beam modulated by a femtosecond laser. We have demonstrated this in the electron storage ring at the Advanced Light Source. Interaction of an electron beam with a femtosecond laser pulse copropagating through a wiggler modulates the electron energies within a short slice of the electron bunch with about the same duration of the laser pulse. The bunch develops a longitudinal density perturbation due to the dispersion of electron trajectories, and the resulting hole emits short pulses of temporally and spatially coherent terahertz pulses synchronized to the laser. We present measurements of the intensity and spectra of these pulses. This technique allows tremendous flexibility in shaping the terahertz pulse by appropriate modulation of the laser pulse.

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The scarcity of intense broadband sources of radiation in the frequency range from 0.3 to 20 THz has led to a high level of innovation in a wide range of technologies in an attempt to fill this gap. Several of the desirable features of such a source include pulses shorter than 100 femtoseconds, synchronization to another ultrafast source ranging from infrared to x-ray wavelengths, and the ability to shape the time envelope of the pulse. Among the technologies is the relatively new development of coherent synchrotron radiation [1] in storage rings. In this Letter, we present a novel method for producing intense temporally and spatially coherent synchrotron radiation pulses at terahertz frequencies from ‘‘holes’’ sliced in the distribution of a high energy electron beam via interaction with a short pulse laser. We report here an experimental demonstration of this technique at the Advanced Light Source (ALS), an electron storage ring operated at 1.5 and 1.9 GeV. This includes measurements of the amplitude and spectral properties of the tunable terahertz pulses. These results complement observations of terahertz signals from sliced beams observed at BESSY II, an electron storage ring in Berlin [2].

With the ability to manipulate the beam distribution on the time scale of several hundred femtoseconds, we show examples of how this could be applied to optimize the pulse energy or obtain a particular field shape by appropriate modulation of the laser pulse.

The interaction of a laser with a relativistic electron beam in a wiggler magnet has been implemented at the ALS since 1999, initially for the production of femtosecond x-ray pulses [3–5]. A 75-fs optical pulse of moderate energy modulates the energy of an ultrashort slice of a stored electron bunch as they copropagate through a wiggler in a storage ring. The energy-modulated electron slice is transversely separated from the main bunch in a dispersive section of the storage ring and used to radiate femtosecond x rays at a bend magnet or insertion device, by collimating the radiation from the unmodulated bunch. In addition, the energy modulation of the sliced electrons creates a small perturbation to the electron bunch longitudinal density consisting of a dip and two side bumps due to the path length dispersion of the electron trajectories, which causes the high and low energy electrons to slip and advance from their original positions while the electron bunch moves from the wiggler to the radiation source. This ‘‘hole’’ gives rise to an electron emission of a temporally and spatially coherent infrared light and therefore provides a natural tunable source of terahertz radiation. The intensity of this radiation scales quadratically with the number of misplaced electrons, which is proportional to the peak bunch current, allowing generation of high peak power pulses.

At the middle of the wiggler, the initial Gaussian electron distribution in the absence of the laser pulse is given by

$$P_0(x_0, x_0', E_0, t_0) = K \exp\left(-\frac{(x_0^2 + x_0'^2 + E_0^2)}{2} - \frac{t_0^2}{2\sigma_{t-e}^2}\right), \tag{1}$$

where x_0, x_0', E_0 are the electron horizontal coordinate and angle and the electron relative energy deviation, respectively, normalized to their respective rms values (σ_x, σ_x', and σ_E), ct_0 is the electron longitudinal position with respect to the bunch center, c is the speed of light, K is a normalization constant, and σ_{t-e} is the rms electron bunch duration. Energy modulation of the electrons copropagating with the laser pulse through the wiggler is described by

$$\Delta E = A_E \cos(\omega_L t_0) e^{-t_0^2/2\sigma_{t-L}^2}, \tag{2}$$

where A_E is the peak amplitude of the energy modulation normalized to σ_E, ω_L is the laser frequency, and σ_{t-L} is the rms width of the laser pulse. Thus, the electron energy after the wiggler is $E_1 = E_0 + \Delta E$. Following interaction with an optical pulse in the wiggler, the temporal distribution of electrons within the bunch is determined by the time-of-flight characteristics of the storage ring lattice and

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energy modulation. The temporal distribution of electrons at the radiating source at time t_R is given by

$$P_R(t_R) = \iiint dE dx dx' P_0(x_0, x'_0, E_1, t_R), \qquad (3)$$

where $t_R - t_0 = (R_{56}E_1 + x_0\sigma_x R_{51} + x'_0\sigma_{x'}R_{52})/c$, where R_{51}, R_{52}, and R_{56} are elements of the ring linear transport matrix and account for the particle path length differences during the electron beam path from the wiggler center to the radiation source due to the electron coordinate, angle, and energy offset, respectively. These control the transformation of the energy modulation into a density modulation and can be varied with the magnetic lattice.

Figure 1(a) shows the calculated electron longitudinal distributions in two locations in the storage ring following the slicing corresponding to the ALS beam lines where we can observe the signal, with distances of 8.4 and 149.5 meters from the wiggler, respectively. The distribution is calculated for several values of A_E with a laser pulse length of $\sigma_{t-L} = 45$ fs. In all cases, electrons with $\Delta E < 0$ accumulate toward the head of the bunch, while electrons with $\Delta E > 0$ accumulate toward the tail of the bunch, creating a dip in a distribution with two side bumps. The uncorrelated energy spread of electrons combined with the path length dispersion cause a smearing of the distribution which is growing with the increased distance from the wiggler, spreading the hole to several picoseconds within a turn and eventually filling it in over tens of turns. For example, for the nominal value of $A_E = 6$, the width of the hole grows from ~90 fs at BL5.3.1 to ~2 ps at BL1.4. Shown in Fig. 1(b) are the calculated spectra of the coherent signal from Fig. 1(a). The spreading of the hole can also be controlled by changing the path length dispersion (momentum compaction). Therefore, the evolution of the frequency content of the coherent signal can be controlled by varying the modulation amplitude and the momentum compaction. Note that the coherent signal from the hole is significantly more intense than the incoherent synchrotron radiation emitted by the other electrons in the bunch.

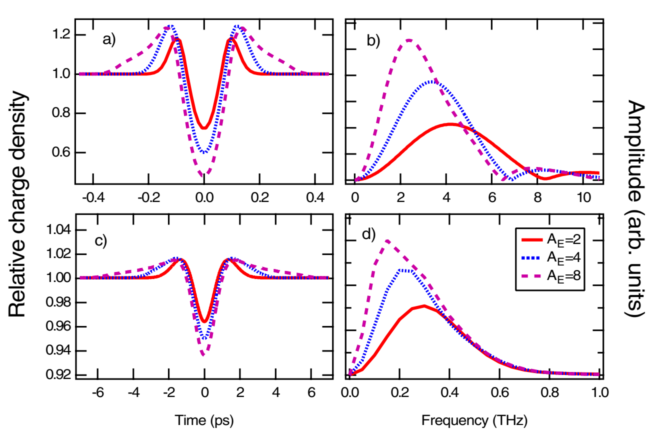

FIG. 1 (color online). Predicted longitudinal distribution of the electron bunch at BL5.3.1 and BL1.4, respectively.

Also note that it is possible to enhance the low frequency part of the spectrum by removing either the negative or positive energy-modulated electrons with a scraper in a transversely dispersive region with a corresponding reduction in the beam lifetime.

Measurements of the infrared radiation at the ALS were performed at two bend-magnet sources located one-half sector downstream (8.4 m) from the wiggler at the beam line 5.3.1 (ultrafast soft x ray, BL5.3.1), and 8 sectors downstream (149.5 m) from the wiggler at the beam line 1.4 (far infrared, BL1.4). The infrared signal bounces from a few mirrors and goes through the Fourier-transform infrared spectrometer (IFS 66V/S, Bruker) with a 6 μm Mylar beam splitter. The signal is collected by a liquid-He cooled bolometer (Infrared Laboratories, Inc.). The bolometer response has a relatively fast rise time and a longer fall time of 0.7 ms defined by its cooling time. A digital oscilloscope is used for time-domain measurements, and a phase sensitive lock-in amplifier (SR844, Stanford) locked to the laser repetition rate is used to improve the signal to noise for spectral measurements.

Figure 2 shows the oscilloscope trace of the infrared signal measured at the two beam lines for the electron bunch currents below a threshold of the bursting instability observed previously [6,7]. The oscilloscope was set in the averaging mode and was triggered by the signal derived from the modulating laser operating at approximately 1 kHz repetition rate. The waveform clearly exhibits the periodicity of 1 ms corresponding to the repetition rate of the modulating laser. The time response of the signal is dominated by the detector response, and the amplitude of the signal, measured as a peak-to-peak value on the oscilloscope, follows a quadratic dependence from the electron bunch current up to the threshold of the bursting instability. Since the first measurements of the infrared signal in

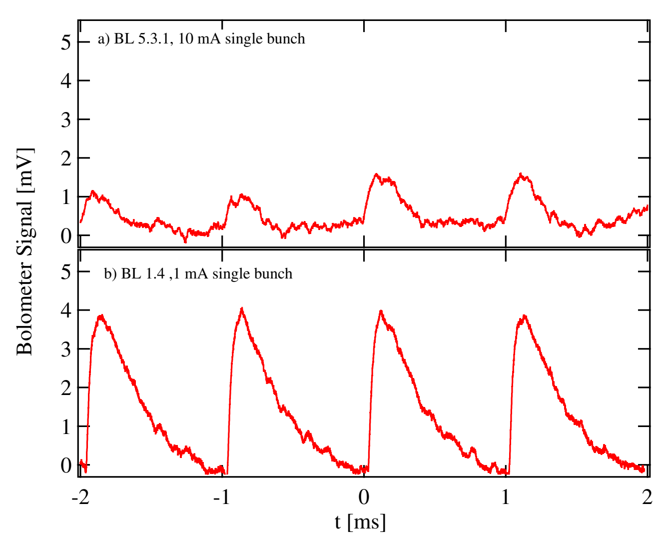

FIG. 2 (color online). Bolometer signal observed at two beam lines with slicing on.

November 2003, the bolometer signal is routinely used as a sensitive monitor for a fine-tuning of the laser beam spatial and temporal alignment during data accumulation in the experiments with femtosecond x-ray pulses. A similar scheme is also being used at other light source slicing experiments [8].

Shown in Fig. 3 are the measured spectra at the two beam lines along with the calculated spectra. The envelope of the measured spectrum at BL5.3.1 shows reasonable agreement but also exhibits significant structure. Much of this can be attributed to absorption by water vapor in the air in the beam transport line. However, careful measurements with argon purging of the beam line did not completely remedy this. Analysis of the light transport with a simplified geometry using the Synchrotron Radiation Workshop code [9] suggests the remaining structure is most likely due to multiple reflections in the beam line and cannot be remedied without a significant redesign of the beam line. It is also possible that multiple reflections within the beam pipe contribute to the structure. The spectrum at BL1.4 is shifted significantly to lower frequency, as expected. Although the light transport at this beam line is free from multiple reflections, the aperture in the ALS vacuum chamber effectively cuts the radiation spectra with wave numbers $<15/\mathrm{cm}$, allowing only a measurement of the higher frequency part of the spectrum. In principle, it is possible to observe coherent signals from the hole over subsequent turns as reported in Ref. [2]. Unfortunately, for ALS parameters, the spectrum for this signal is pushed below the cutoff frequency of our measurement setup, effectively filtering it from view. The rate of spreading of the hole can be reduced by operating the storage ring lattice at lower momentum compaction, allowing the signal to be observed over a greater number of turns.

We also measured the coherent radiation spectrum as a function of the laser and storage ring parameters for consistency. Variation of the bunch charge quadratically varies the intensity of the spectra, while the laser pulse width and modulation depth shifts the spectrum. These measurements also support the notion that much of the structure in the spectrum was due to the beam line, since the nulls did not shift with the spectrum envelope. We also doubled the path length dispersion (momentum compaction) of the storage ring lattice from a value of 0.001 37 to 0.0027. The spectra shift was qualitatively consistent with expectations. Note that the higher momentum compaction lattice has a higher microbunching threshold by a factor of 2.8, allowing measurement of the radiation from the slicing at a correspondingly higher bunch current and a factor 8 larger coherent signals.

Even with the poor terahertz transmission of the ALS beam lines, we have demonstrated the technique described above for generating ultrafast terahertz pulses. We can now consider possibilities for optimizing such a source for various applications. For example, using parameters for a proposed storage ring [10], we have optimized the energy

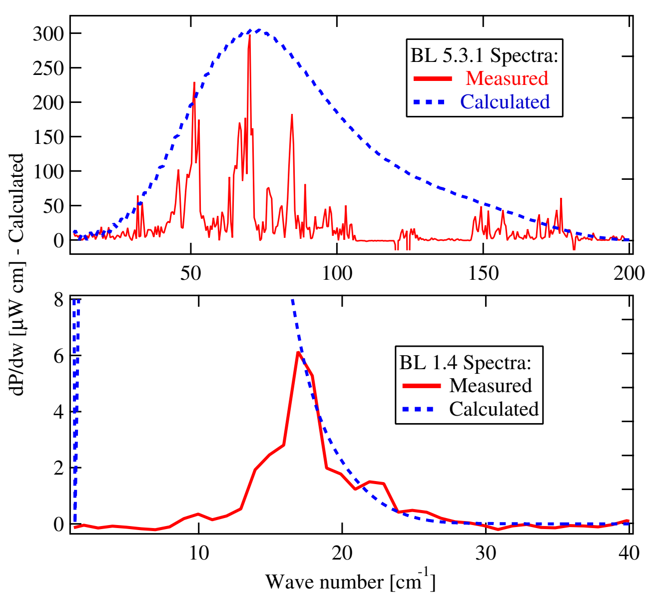

FIG. 3 (color online). The spectral measurement of the infrared signal at BL 5.3.1 and BL1.4.

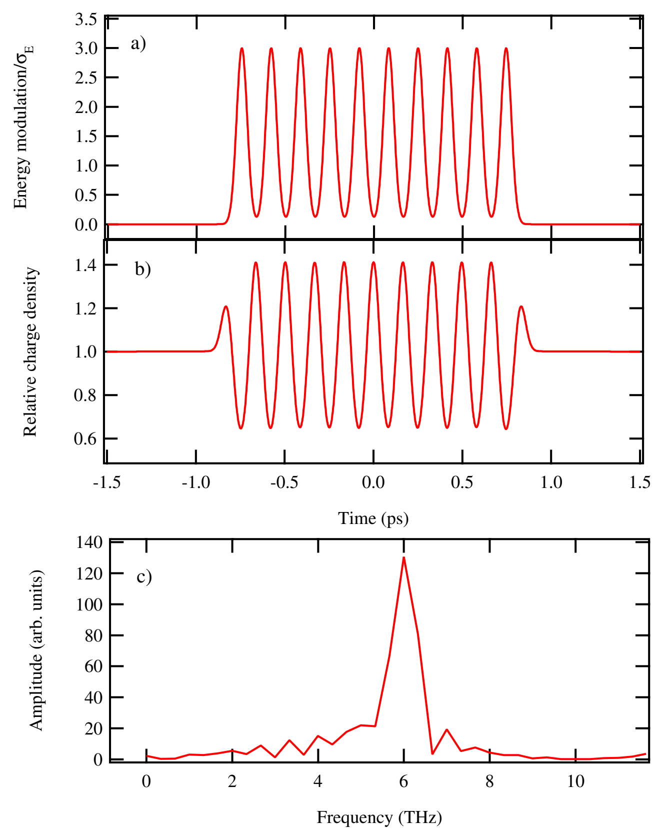

FIG. 4 (color online). Tailored slicing using a laser pulse train. (a) Laser intensity in units of σ_E for a 10 period pulse train. (b) Resulting longitudinal beam distribution. (c) Spectral response.

per pulse and bandwidth of such a source. For electron bunches with rms lengths of 3 psec and 2.2 nC sliced by a laser with 75 fsec (FWHM) and $A_E = 6$ at a distance of 2.5 m from the modulation, we calculate an energy per pulse of 8.5 μJ with a bandwidth up to 20 THz. This mode of operation could occur at a repetition of up to 10 kHz using existing laser technology.

One of the most interesting possibilities is the ability to tailor the electric field of a terahertz pulse by appropriate modulation of the slicing laser. One application for this is the use of optimal control [11] of the pulse shapes to enhance chemical reactions. As an example, we show the bunch distribution and electric field for a bunch sliced with a series of 10 Gaussian laser pulses separated by $5\sigma_{t-L}$ in Fig. 4. In this example, variation of the delay, intensity, and number of laser pulses allows continuous tuning of the frequency of the radiation. This distribution was originally suggested by Litvinenko [12] as a means of generating high intensity terahertz radiation but required a millimeter wave bunching system. Note that the feasibility of this approach does not require any significant advance in beam or laser technology and could be adapted to many of the third generation light sources. This approach can also be adopted for light sources based on single pass and energy recovery linacs, either as a source of terahertz radiation synchronized to the x-ray pulse or for time fiducialization.

In summary, we have observed and characterized coherent terahertz radiation from a relativistic electron beam after interaction with an intense pulse laser beam in a 1.5 GeV storage ring. Besides providing a diagnostic for the slicing techniques, this provides a broadband, tunable, coherent, synchronized source for terahertz time-domain spectroscopic applications. Furthermore, there are further possibilities of tailoring the terahertz pulses for specific applications.

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