

GENERATION OF TERAHERTZ RADIATION BY MODULATING THE ELECTRON BEAM AT THE CATHODE

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Abstract

A bunched electron beam can be used to generate coherent radiation in a particle accelerator. This experiment, a collaboration between the University of Maryland and the Source Development Laboratory at Brookhaven National Laboratory, uses a drive laser modulated at terahertz frequencies in an RF-photoinjecting electron accelerator to produce a bunched beam at the cathode. The experiment is designed to determine if such a scheme could be used to develop a compact, high power terahertz emitter. After acceleration to approximately 73 MeV, a mirror intercepts the beam. The backwards transition radiation from the mirror is measured with a bolometer. The experiment was conducted at various modulation frequencies and levels of charge.

INTRODUCTION

Shaping the profile of a laser pulse incident on a photocathode is important for many types of radiative devices. In some free electron laser applications, smoothing the profile may be necessary to prevent unwanted emission of radiation. In other cases, laser modulation can be used as a radiation source. This work explores using a modulated drive laser to produce a similarly modulated electron beam in order to generate terahertz radiation. There are many potential applications for terahertz light including exploration of vibrational modes in DNA and proteins, weapons and explosives detection, and communications. A review of some applications and available sources of terahertz radiation is given by Siegel [1].

In general, the radiation emitted by a bunch of electrons can be expressed as

$$\frac{d^2W}{d\omega d\Omega} = \frac{d^2W_1}{d\omega d\Omega} [N_e + N_e(N_e - 1)F(\omega, \theta, \phi)] \quad (1)$$

where N_e is the number of electrons, and $F(\omega, \theta, \phi)$ is the form factor. The form factor is a number between zero and one that depends on the geometry of the electron beam. A tightly bunched beam (the bunches are much

smaller than the wavelength separating the bunches) will yield a form factor of 1, while an unbunched beam will yield a form factor of zero.

The single particle term, $d^2W_1/(d\omega d\Omega)$ applies to any radiative mechanism, such as a wiggler, a bend magnet, or a transition radiator. While this experiment focuses on a transition radiator, injecting a prebunched beam into a wiggler causes it to reach saturation faster than an unbunched beam (Fig. 1)

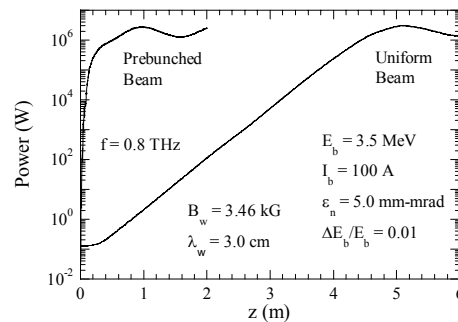


Fig. 1: Comparison of the growth of 0.8 THz radiation in WIGGLIN simulation using both prebunched and uniform beams.

This experiment, conducted at the Source Development Laboratory (SDL), at Brookhaven National Laboratory, used a modulated Ti:sapphire drive laser to produce a modulated electron beam. The electrons are accelerated to approximately 73 MeV, and transition radiation is produced by interaction of the beam with a 2cm diameter mirror placed at 45 degrees with respect to the beam direction. The terahertz light passes through a transport system to a bolometric detector. Information about the spectrum of the radiation is obtained by using various terahertz filters.

In an ideal case, a periodic train of short electron bunches would be accelerated to the radiator. One example of this type of profile is shown in Fig. 2. The expected spectrum of the terahertz radiation that could be emitted by such a beam is shown in Fig. 3, depicting cases for 1, 2, 4, and 8 bunches. Note that a single short bunch produces a broadband coherent signal, whereas the bunched cases result in a more narrow band source.

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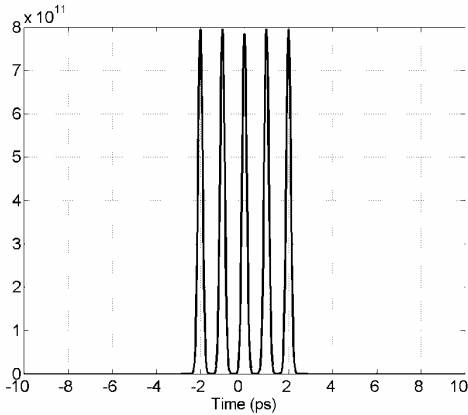


Fig. 2: "Ideal" train of short electron bunches

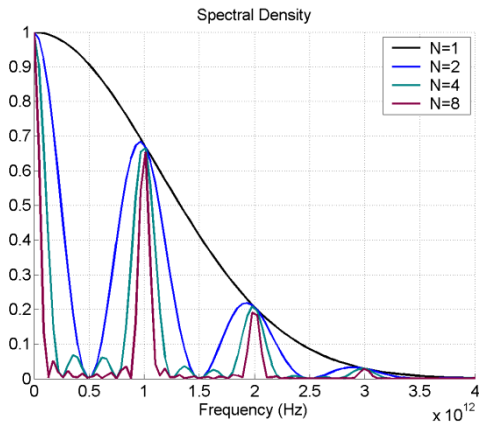


Fig. 3: Calculated spectrum for bunch train of 1,2,3 and 4 equally spaced bunches.

Assuming 1 nC of charge and a the finite metal disc in the SDL as a transition radiator, the total backwards transition radiation is calculated to be 112.2 μJ , 54.8 μJ , 25.9 μJ , and 12.1 μJ for $N=1, 2, 4,$ and 8 respectively.

This experiment focuses on generating a narrow band source, in contrast to other electron beam-based broadband coherent terahertz sources including one demonstrated at the Source Development Laboratory [2] and the Thomas Jefferson National Laboratory [3].

DRIVE LASER MODULATION

The drive laser at the Source Development Lab is based on a commercial 800 nm Ti:sapphire laser. The system produces a 100 fs pulse. A chirped pulse amplification system increases the pulse energy, and it is frequency tripled to 266 nm. In normal operation, a multipicosecond UV laser pulse is directed to the cathode. A scanning cross correlator is used to measure the time profile of the incident laser pulse [4].

In this experiment, an interferometer was used in order to induce drive laser modulations. This technique

succeeded in generating several different pulse train configurations, varying in modulation frequency and number of bunches. Two representative cross correlations of obtained UV laser pulses follow in Fig. 4.

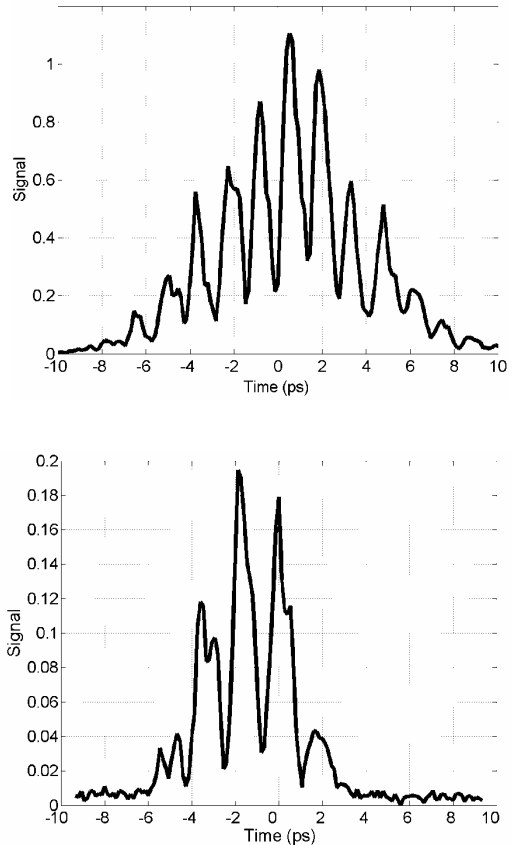


Fig. 4: Examples of UV drive laser cross correlations.

ELECTRON BEAM MEASUREMENTS

After acceleration, the electron beam longitudinal profile is measured. The measurement is made by applying an energy chirp, passing the beam through a magnetic dipole, and examining the beam on a screen. Measurements are made using the RF zero phasing technique, but it has been shown that energy modulation may appear as density modulation using this technique [5]. Varying the energy chirp allowed a tomographic reconstruction technique [6] to be applied to a series of projections in order to recover a time profile of the electron bunch.

Fig. 5 shows two examples of electron beam profiles for different charge levels. Notice that as the charge increases, the entire bunch spreads in time and each individual peak also expands. This has a corresponding effect on the spectrum of the terahertz radiation.

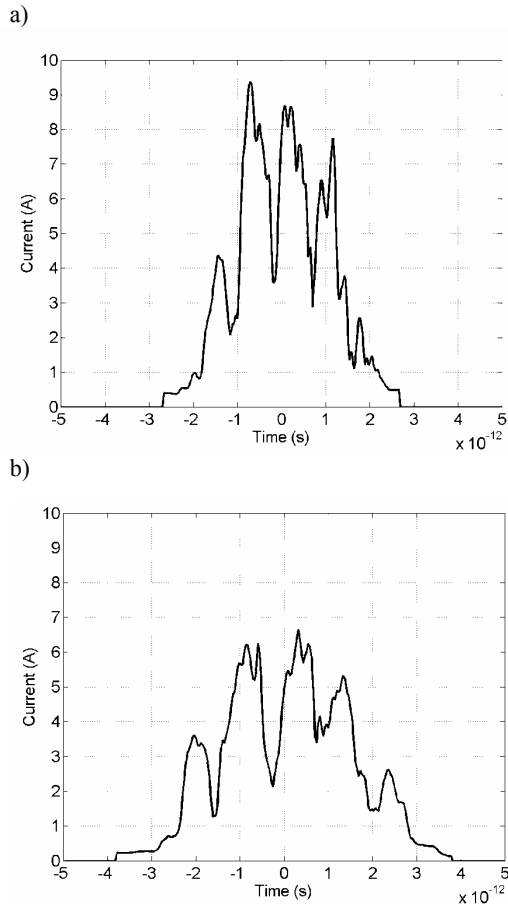


Fig. 5: Two electron beam profiles from tomographic reconstruction corresponding to the second laser pulse shown above. The total charge in (a) is 20 pC and the total charge in (b) is 65 pC.

TERAHERTZ MEASUREMENTS

As a first step for characterizing this source, it was important to determine the energy and spectrum of the terahertz light. Although the spectrum could not be measured directly, four filters were used to sample the the spectrum. The filters are a metal mesh design, and their transmission characteristics were measured on the U12 IR beamline at the National Synchrotron Light Source. The measured filter transmission curve is shown in Fig. 6.

Each of the filters is referred to by a color for convenience. For each charge and modulation setting, the transition radiation produced by the electron beam was measured with a helium cooled bolometer, and with each filter. The expected amount of energy was calculated using equation (1) to determine the expected spectral density per solid angle, taking into account losses due to absorption in air and the geometry of the transport system; the appropriate filter transmission curves were applied, and the total integrated energy was compared to the

measurements at the detector. One result of such a comparison is shown in Fig. 7.

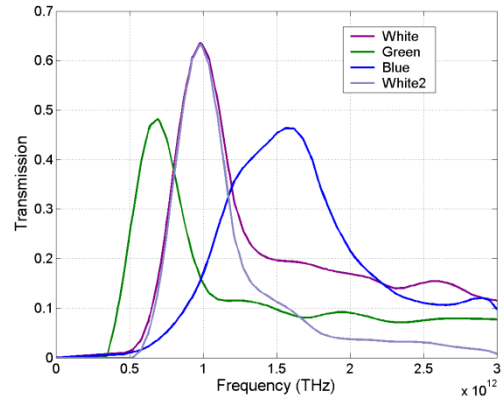


Fig. 6: Characterization of the terahertz filters

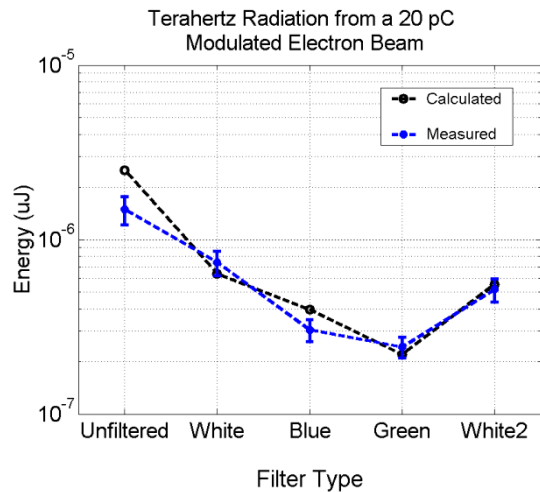


Fig. 7: Terahertz energy measured/calculated at the detector

Agreement between the experimental measurements and theoretical calculations are an indicator that the calculated spectrum is representative of the actual terahertz radiation spectrum produced by the electron beam.

Fig. 8 shows the spectral density calculated from the two electron beam profiles shown above. Note how increasing charge affects the electron beam density profile, and therefore the spectrum.

The total energy arriving at the detector for the 20 pC case was 1.5 pJ (measured) compared to 2.5 pJ (calculated). Estimation of losses in the transport system suggest that the terahertz light exiting the accelerator window is approximately 0.4 nJ. In the 65 pC case, the total energy arriving at the detector was 5.4 pC, which corresponds to 2.4 nJ at the accelerator window.

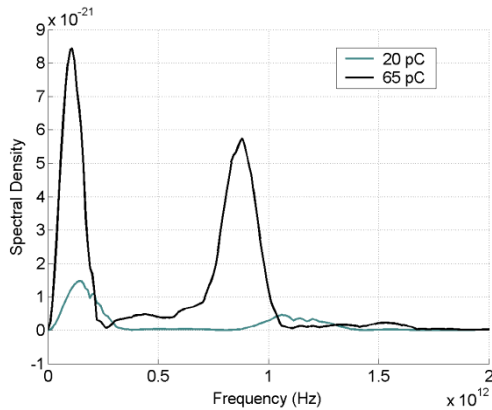


Fig. 8: Achieved Spectral Density

CONCLUSION

This experiment indicates that information from drive laser fluctuations are passed on to the electron beam and can be detected after acceleration. Although the total energy measured at the detector was small, one might achieve higher single shot terahertz pulse energy, as well as a narrower bandwidth, by implementing a better laser control system or a customized electron beam transport system in order to generate a pulse train closer to the ideal case.

One of the problems with pre-modulation of the electron beam is washout of the density modulation. It is important to note, however, that there is still evidence of the initial density modulation in the energy-time phase space even if the density modulation is washed out. This means that it may be possible to recover this density modulation through an appropriate dispersive mechanism.

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