Coherent THz Pulses from Linear Accelerators

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Abstract

Coherent THz pulses are being produced at several facilities using relativistic electrons from linear accelerators. The THz pulses produced at the Brookhaven accelerator have pulse energies exceeding 50 μJ and reach a frequency of 2 THz. The high repetition rate of the Jefferson Lab accelerator leads to an average THz power of 20 watts. Possible uses for these high power pulses are discussed.

Coherent Synchrotron Radiation

As first demonstrated by Nakazato and co-workers[1], short bunches of relativistic electrons experiencing a common acceleration radiate coherently for wavelengths greater than the bunch length. Subsequent studies confirmed the detailed relation between the spectral content and electron bunch longitudinal density[2], and it was recognized that this coherent radiation could be a new source of broadband millimeter and submillimeter waves[3].

The characteristics of these pulses are similar to those produced by ultra-fast lasers and photoconductive switches. The coherent radiation appears as a transform-limited pulse, with an intensity that scales as N^2 (where N is the number of electrons in the bunch), giving rise to a coherent enhancement factor of N when compared to the incoherent case. However, compared to pulses produced with photoconductive switches, the power emitted by relativistic electrons can be significantly larger, even for the same acceleration. This can be seen from Larmor's formula,

$$Power = \frac{2e^2a^2}{3c^3}\gamma^4$$

which shows that the radiated power is proportional to the 4th power of relativistic mass enhancement factor γ.

The NSLS DUV-FEL

The Deep Ultra-Violet (DUV) FEL at Brookhaven delivers up to 500 pC of charge in a ~ 300 fs long bunch at a pulse repetition rate of about 3 Hz. With these bunches, coherent radiation pulses in the THz range have been produced as both dipole (bending magnet) radiation and also as transition radiation (when the electron beam is incident onto a metal mirror). The THz radiation is extracted through a quartz window and measured either directly with a pyroelectric pulse energy detector (Molectron, Inc.) or transported via copper lightpipe to a spectrometer located externally to the linac enclosure. The spectrometer is a lamellar grating interferometer[4], optimized for the spectral range from 1 cm^{-1} to 100 cm^{-1}. For convenience, a liquid helium cooled bolometer is used for detection, although a greater than 30-fold reduction in THz pulse intensity is needed for the detector to operate properly. The measured spectrum for a ~ 300 fs duration electron bunch is shown in Fig. 1. The useful intensity reaches to 60 cm^{-1}, or nearly 2 THz. The γ^4 power enhancement gives rise to an impressive amount of energy, easily exceeding 1 μJ per pulse. Indeed, we have observed pulses energies well over 50 μJ, which is more than sufficient for a variety of pump-probe experiments. The electric and magnetic fields associated with such a pulse are also significant when the radiation is focused into a diffraction-limited volume. Rough estimates suggest E-fields of greater than 10^8 V/m should be achievable. The magnetic field associated with such a pulse approaches 1 T. In both cases, the duration of these intense fields would be on the order of 1 ps.

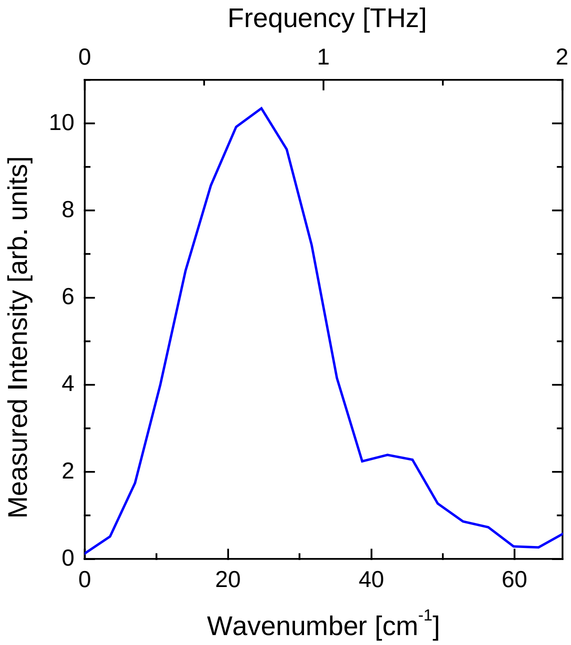

Fig. 1. Measured spectral intensity for the coherent transition radiation produced by ~ 300 fs long electron bunches from the NSLS DUV-FEL linac.

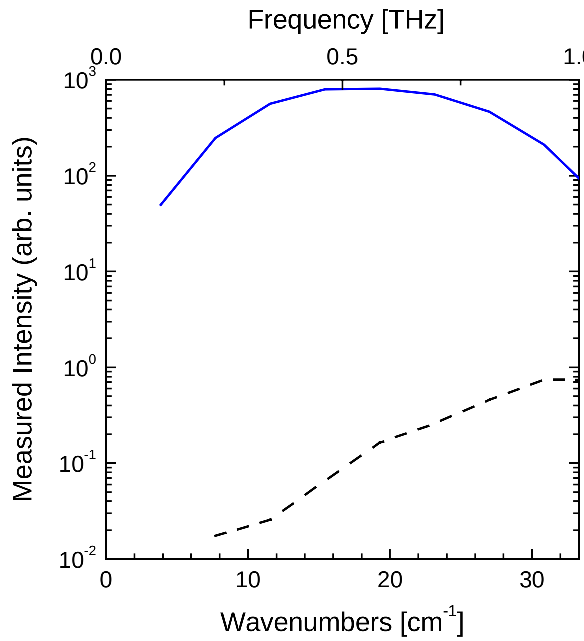

Fig. 2. Comparison of the average spectral intensity for the coherent dipole radiation from the JLab ERL (solid curve) and a conventional globar source (dashed curve).

The Jefferson Lab Energy Recovery Linac

The Jefferson Lab energy recovery linac (ERL) serves as the electron beam source for a high-power infrared FEL, but it is also a prodigious source of THz power in the form of dipole synchrotron radiation[5]. At the location where the THz is extracted, the electron bunches are slightly longer, and the charge per bunch is slightly less than for the NSLS linac, but this is more than compensated by the much higher pulse repetition rate of 38 MHz. Thus, even when the energy per pulse is less than 1 μJ, the average power can be 10s of watts. The spectrum of emitted light for a much lower repetition frequency of 584 kHz (and therefore lower average power) is illustrated in Fig. 2, as measured with a Nicolet FTIR spectrometer. The measured signal for the spectrometer's globar source is shown for comparison. Work is beginning at Jefferson Lab to construct laboratory space dedicated to research using this high power THz source.

Summary and Outlook

Coherent THz pulses from linear accelerators possess a number of unique advantages over other broadband THz pulse sources, in particular, very high peak intensity along with high average power. These accelerators have been developed for free electron lasers and already exist at a number of institutions through the world. Research is underway to determine the utility of these pulses for spectroscopy, creating coherent excitations, and for imaging.

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