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Very High Power THz Radiation Sources

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Abstract. We report the production of high power (20 watts average, ~1 Megawatt peak) broadband THz light based on coherent emission from relativistic electrons. Such sources are ideal for imaging, for high power damage studies and for studies of non-linear phenomena in this spectral range. We describe the source, presenting theoretical calculations and their experimental verification. For clarity we compare this source with one based on ultrafast laser techniques.

Key words: Coherent, synchrotron radiation, terahertz

1. Introduction

The Jefferson Lab Free Electron Laser (FEL) [1] in Newport News, Virginia, USA delivers sub-picosecond pulses of light in the 1–6 micron range, with repetition frequencies up to 75 MHz and 10–20 microjoules per pulse. Average output powers can be as high as 2 kilowatts.

Here we describe a program to develop, characterize and utilize broadband THz sources at this FEL facility. We do not use the laser itself, but instead use the electron accelerator on which it is based. This accelerator is the first of a new generation of photo-injected Energy-Recovered, (superconducting) Linacs (ERL). When the electron bunches were steered around a chicane with dipole magnets they emitted synchrotron radiation.

We now describe what is new and different about this synchrotron radiation, and to do so we refer to Figure 1. The basic process for light generation is that it can be understood as the power spectrum (Fourier transform) of the electric field as a function of time [2, 3]. Thus, one electron passing an observer (a) gives a changing electric field as a function of time (b), which yields the power spectrum (c). When we now consider the real situation in which we have many electrons separated in space, we see from Figure 2a that the electric fields for wavelengths shorter than the bunch length add incoherently, and the total power for N electrons is simply N times the one electron value. However, if the same electrons are bunched tightly

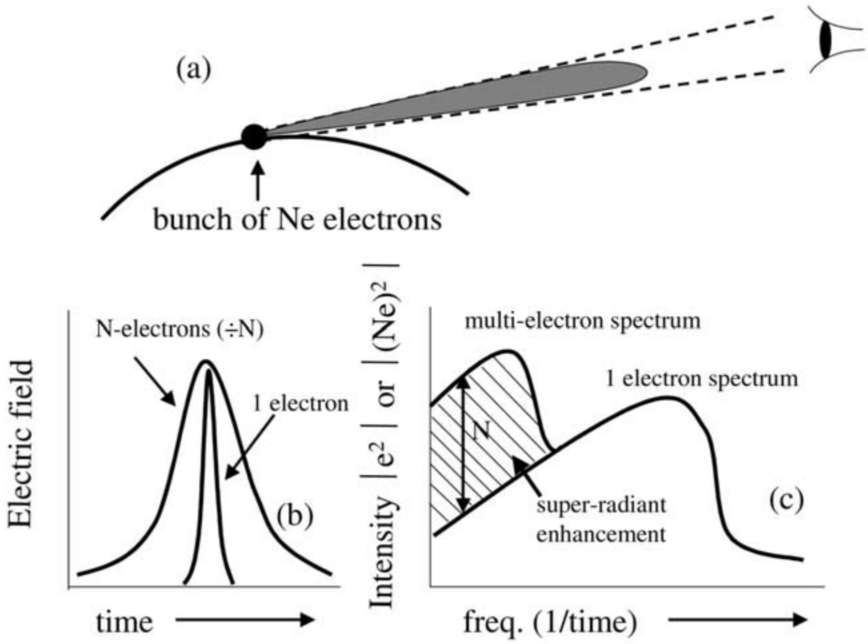

Figure 1. Schematic of the generation of light by relativistic electrons. In (a) the electric field is shown strongly collimated in the forward direction due to relativistic effects. For both one electron and a bunch of N electrons, an electric field is generated as a function of time (b), which yields a broad power spectrum as shown in (c).

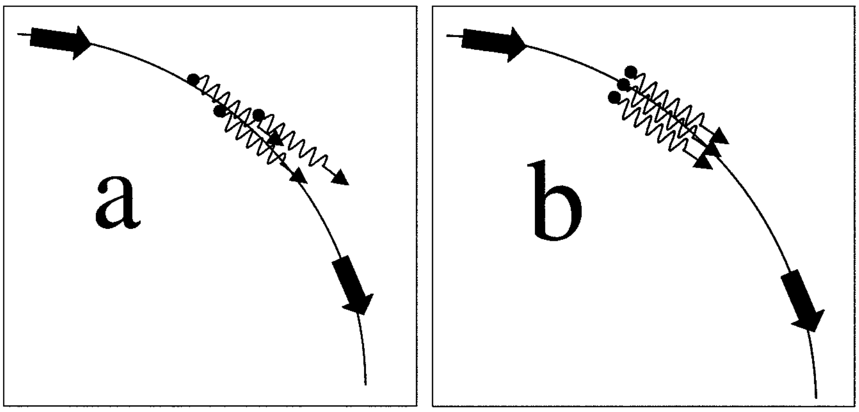

Figure 2. Illustration of the incoherent emission of electrons dispersed in space (a) and compared to the situation (b) in which they lie spatially within a wavelength (longitudinally) of the light being observed. In the latter case the electric fields add coherently and the intensity scales as the square of the number of electrons.

with respect to the wavelength of light being emitted, Figure 2b, the fields add coherently so that the intensity scales as N^2. This enhancement is very large since the number of electrons per bunch is of order 10^9 in our case. Referring back to Figure 1, we see both the 1 electron and multielectron spectra schematically.

The situation is handled theoretically by considering that for a 'bunch' of electrons, there are 2 time-scales that control the pulse duration; one is the bunch length and the other is the time for the relativistically compressed acceleration field from each electron to sweep past. The latter is given approximately by [2] $\delta t = 4\rho/(3\gamma^3 c)$ and determines the spectral range emitted by each electron. The bunch length determines the spectral range over which the coherent enhancement occurs. In general, when an electron bunch length approaches that of the wavelength of the light being emitted, the entire bunch radiates coherently [4, 5]. For the special case of an electron energy of 10 MeV, and with $\rho = 1$ m, we obtain a single electron δt of about 500 fs, which is actually comparable to the bunch length.

Such coherent synchrotron radiation has been observed from electrons accelerated in linacs [6–8], from compact waveguide FELs [9] and from magnetic undulators [9–11]. Coherent THz light has also been discussed and observed from electron bunches in storage rings [12–17], and active programs to study THz radiation from linacs or storage rings are underway at many laboratories. In addition, programs are underway at ENEA-Frascati to generate broadband THz radiation by exploiting the distinctive properties of waveguide FELs which arise when the electron velocity is close to the group velocity of the wave packet[18]. Some linacs can create very short bunches ($<$ 1 ps) and produce coherent radiation up to a few THz, but most are limited to repetition rates of a few Hz, so the average power is quite low. The repetition rate for storage rings is on the order of 100 MHz, but the electron bunches are significantly longer ($\sim$100 ps) due to longitudinal damping through synchrotron radiation emission. Thus the emission is limited to the very low frequency regime (far-IR), or arises from instabilities that momentarily modify the bunch shape.

The JLab ERL accelerator system overcomes some of the limitations of conventional linacs and storage rings. Electron bunches as short as $\sim$ 500 fs are produced by the standard technique of energy modulation (chirping) followed by compression in the dispersive region of a magnetic chicane [19]. The time for an electron bunch to pass through the accelerator is less than 1 microsecond, thus longitudinal damping is negligible. Unlike most linacs, however, it operates at a very high repetition rate (continuous at up to 75 MHz) by using superconducting RF cavities and recovering the energy of the spent electron bunches [1], so that the average current is orders of magnitude higher than in conventional linacs.

It may be helpful to compare THz radiation produced by this technique of coherent synchrotron radiation with an Auston switch source [20, 21]. It should be noted, however, that this comparison, while conceptually useful, will not stand deep quantitative scrutiny. In both cases a short pulse from a mode-locked laser strikes a GaAs wafer, generating charge carriers. Thus the number of radiating charges is

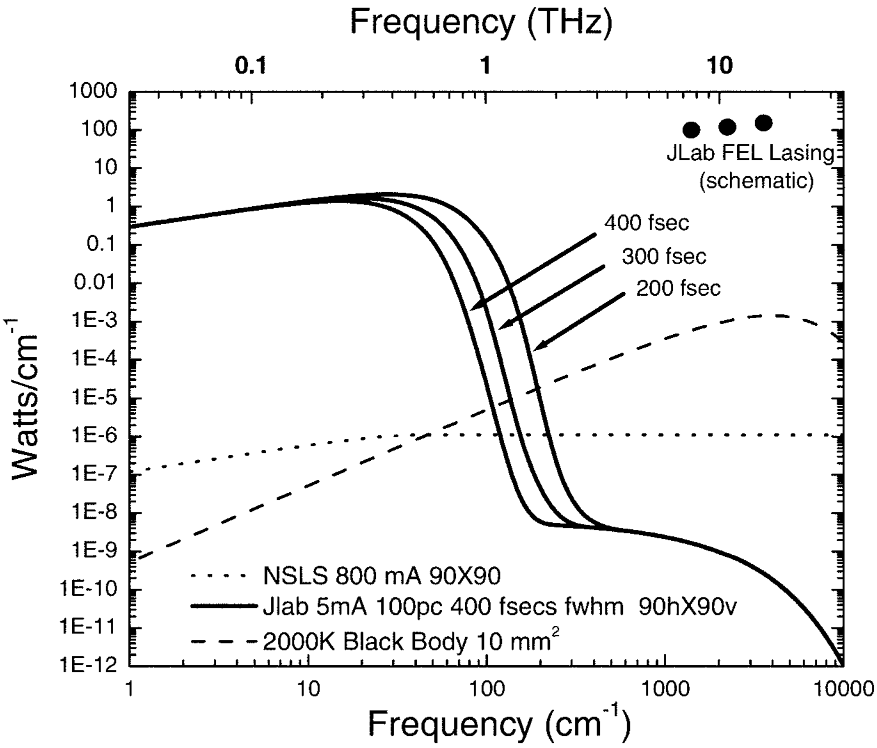

Figure 3. Calculations of the power emitted by 3 sources. For the Jlab source the calculations were performed for several full width half maximum values of bunch length given in fsecs to illustrate the dependence of the enhancement on this parameter.

comparable. We can therefore compare the power produced per electron, and use Larmor's formula [2] for the radiated power, which in CGS units takes the form:

$$\text{Power} = \frac{2e^2a^2}{3c^3}\gamma^4 \tag{1}$$

where e is the charge, a is the acceleration, c the speed of light and γ is the ratio of the mass of the electron to its rest mass. For a conventional Auston switch based on a laser pulse striking GaAs, the acceleration felt by the electron is quite similar to the transverse acceleration felt by an electron in the chicane bending magnet in our accelerator, but in our case γ is 75, yielding a considerable enhancement.

2. Calculations and Results

Details of the theory have been presented elsewhere [22], and in Figure 3 we present calculations of the total power emitted by 200,300 and 400 fsec fwhm electron bunches in units of (average) watts/cm^{-1} over the range 1–10,000 cm^{-1}, or 1 centimeter to 1 micrometer. We assumed the electron bunches had an energy of

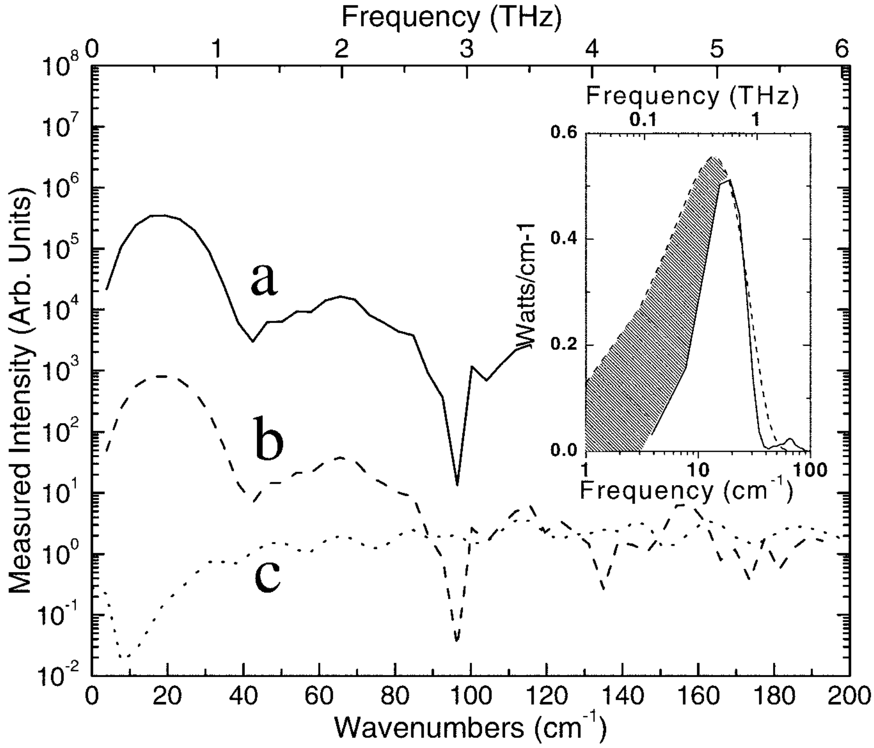

Figure 4. Intensities of light for (a) the Jlab source scaled to 4.6 mA, (b) the actual measurement at 0.02 mA and (c) the 1400K thermal source. In the inset we show the measurement on an absolute scale, solid line, compared with the calculation, dashed line. The discrepancy shown by the hashed area is due to diffraction as described in the text.

40 MeV, carried a charge of 100 pC, and that they passed through a 1 m radius bend at a 37.4 MHz repetition rate. In the same figure we compare 2 other broadband sources, namely a 2000 K thermal source, and the National Synchrotron Light Souce U4IR facility [23] at Brookhaven National Laboratory. The superiority of the JLab ERL and the onset of the coherent emission are evident.

In Figure 4, we present the results of our measurements and in the inset, a comparison with our calculation. The spectral content of the emitted THz light was analyzed using a Nicolet 670 rapid-scan Michelson interferometer and detected using a 4.2K Infrared Laboratories bolometer. Our collection angle was 60 $\times$ 60 milliradians and the extraction window was quartz. We were able to determine the absolute power in 2 ways, one using a calibrated pyroelectric detector, and one by comparing our spectra with that from a 1300 K thermal source. For the comparison to calculated values in the inset of Figure 4, the data was scaled on the basis of the absolute power measurements and shows quite a good quantitative agreement.

In the inset of Figure 4, the spectral onset of the super-radiant enhancement of the THz light is clearly seen on the high frequency side. The onset shape is also seen to match closely the theoretical predictions. Note that there is a severe discrepancy on the lower frequency side due to diffraction effects. This can be understood in the following way. At 10cm^{-1} and with an f/17 beam, the diffraction-limited source size is 17 mm, almost the same as the extraction optics. At 1 cm^{-1}, the diffraction-limited source size would, at 170 mm, be more than 3 times larger than the vacuum chamber containing the electron beam.

We are now planning an upgrade to the facility at Jefferson Lab in which we will considerably upgrade the THz extraction aperture. The upgraded accelerator will also carry twice the average current and have the capability of stronger bunch compression which will lead to spectra extending to higher frequencies.

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