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Evolution of the high power THz source program at Jefferson lab

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Abstract

We report the evolution of the high power THz source program at Jefferson Lab. The source is based on coherent synchrotron radiation in which short bunches of relativistic electrons radiate when traversing a dipolar magnetic field. In our first accelerator we produced 20 W of broadband THz light. Our upgraded accelerator with higher current and improved THz extraction optics which will considerably enhance the output power to >100 W. In this paper we describe the source in some detail and present theoretical calculations for the upgrade.

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1. Introduction

The THz source is located at the Free Electron Laser (FEL) facility at Jefferson Lab [1]. The FEL requires ultrashort (<ps) bunches of relativistic electrons which emit synchrotron radiation during passage through the dipole steering magnets of the optical chicane required for the FEL cavity. Since the electron bunch lengths are of the order of the wavelengths of THz light, the electrons radiate in phase with each other [2] to yield a multiparticle enhancement proportional to the number of electrons in a bunch, which is in the 10^{8-9} range. In our first machine [1,3,4] the electron beam had an energy of 48 MeV and an average charge of 60 pC/bunch at 75 MHz, for a current of 5 mA. Optically we were able to extract 60×60 mrad of light from a 1 m radius bend. We are in the process of com-

missioning a new machine in which the energy is >100 MeV, the charge per bunch is 135 pC ($\sim 10^9$ electrons) at 75 MHz, and from which we can extract 170×170 mrad of light, 50 mrad before the start of bend to 120 mrad into the bend.

The high THz power is a result of the relativistic enhancement, given in Eq. (1) (below) as γ^4 , where γ is the ratio of the mass of the electron to its rest mass. Since the rest mass of an electron is 511 keV/c², $\gamma = 200$ for a 100 MeV beam and the enhancement is 200^4 or $\sim 10^9$, consistent with the argument a few lines above. In CGS units Larmor's formula [3] it takes the form

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

where e is the charge, a is the acceleration, and c the speed of light.

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2. Theory and calculations

The full theory is based on Eq. (1) but developed to yield both spectral and spatial distributions of intensity [3,5]. Kim [6] first showed the practical extensions to the theory of [5] to calculate actual emitted power as a function of bandwidth, polarization, wavelength and emission angle. A more tutorial description of the procedures has been presented by Hulbert and Williams [7]. The theory of infrared synchrotron radiation emission was first presented by Duncan and Williams [8] and further refined by Hirschmugl et al. [2] to take account of multiparticle effects including FEL theory and THz emission. For this there are two time-scales that govern the emission, one being that of the passage of a single electron, and the second being the time of passage of the bunch.

Based on the formulae in [2,3] and [7], in Fig. 1 we present calculations of the total power emitted by a 300 fs fwhm electron bunch in units of (average) W/cm^{-1} over the range $1\text{--}10,000\text{ cm}^{-1}$, or 1 cm to $1\text{ }\mu\text{m}$ wavelength for the FEL upgrade. The considerable improvement in performance compared to our previously reported [4] 20 W THz source is shown by comparison in the same figure with calculations for that earlier source. Also, for reference in the same figure we compare a 2000 K

thermal source, and a synchrotron radiation source, namely the National Synchrotron Light Source U4IR facility [9] at Brookhaven National Laboratory. It is to be noted that the accelerator-based sources all emit into narrow angular cones of opening angle α determined approximately by the diffraction condition ($\alpha = s/\lambda$) where s is the source size and λ the wavelength, whereas the 200 K thermal source emits into 2π steradians. Therefore the brightness (source intensity divided by the product of source size and emission angle) is far superior for these sources. In any case, even in terms of power, the superiority of the JLab ERL and the onset of the coherent emission are evident.

In Fig. 2 we extend our calculations for electron bunches of different lengths. The calculations clearly show the dependence of the emission on the length of the electron bunch both in terms of spectral coverage and total power, and in fact, for 100 fs fwhm bunches the power exceeds 1 kW with useful power up to $>10\text{ THz}$.

3. Conclusions

We have shown that the short bunches in the new generation of sub picosecond energy recovery systems yield broadband high brightness far-IR

Fig. 1. Calculations of emitted power from four different broadband sources. The numbers for the JLab and NSLS sources refer to the properties of the electron bunches and/or the beam current and the collection angles for the radiation.

Fig. 2. Calculations of emitted power from the Jefferson Lab THz source for three different values of the electron bunch length all for an electron bunch charge of 135 pC and 75 MHz repetition frequency.

radiation with about 10 W/cm^{-1} of average power into the diffraction limit. If this power is delivered in 500 fs fwhm pulses every 13.3 ns, the peak power is $\sim 2 \times 10^4$ higher than this. Further, we note that since the electron bunch has lateral dimensions that are smaller than the wavelength, full spatial coherence exists.

High power sources such as this are expected to play a critical role in areas of imaging [10] and non-linear optics. In order to facilitate these applications we are currently designing an optical transport system to deliver this beam to a laboratory.

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