Synchrotron radiation from an electron beam

V. B. Pathak, V. K. Tripathi, R. A. Fonseca, and L. O. Silva

Phase-matching a co-propagating electromagnetic wave and electron beam as they pass through an obliquely modulated plasma causes the beam to emit terahertz radiation.

Coherent radiation generation, specifically in the terahertz (THz) regime, is of great interest for its potential applications in chemical and security identification,\(^1\),\(^2\) biological imaging,\(^3\) and remote sensing.\(^4\) Terahertz imaging is a promising non-destructive technique for detecting many common explosives that have resonant peaks in the THz region (including those known as RDX, HMX, PETN, and TNT and commercial explosives based on them, such as those commonly known as PE-4 and Semtex). Some existing THz radiation generation schemes involve the interaction of femtosecond laser pulses\(^5\) and energetic electron beams\(^6\) with plasma. Plasma has an ability to sustain very high fields, and thus can provide high gain and easily handle very high-power radiation. However, THz radiation sources based on femtosecond lasers are generally limited to energies of the order of a few microjoules per pulse at present.\(^5\)

A relativistic electron beam can provide higher energies per pulse.\(^6\)–\(^8\) It is possible to generate a high-energy, short-wavelength electromagnetic wave in a periodic dielectric material, when a moderately energetic electron beam co-propagates with an electromagnetic wave, and the electromagnetic wave is amplified at the expense of the electron beam energy.\(^9\)

Another method of generating tunable narrowband THz radiation is by co-propagating an electron beam and a modulated long laser pulse through magnetic undulators\(^10\) (periodic structures of dipole magnets, with alternate static magnetic fields along the length of the undulator). The electron beam acquires a static density modulation as it passes through the undulators. Its modulation period depends on the laser modulation period and the beam velocity. If the electron beam is then deviated by a bending magnet, the different electron trajectories cause the phase-space distribution to tilt, and the beam acquires a transverse modulation component. As a result, the beam emits synchrotron radiation in the THz range.

Figure 1. Variation of \(\lambda_q\), the plasma modulation wavelength, with (a) plasma density \((n_0)\) at beam relativistic factor \(\gamma_{0b} = 4\), and (b) with \(\gamma_{0b}\) for \(n_0 = 5 \times 10^{15} \text{cm}^{-3}\). For both plots, the electromagnetic wave (wavelength, \(\lambda\), is 300\(\mu\text{m}\)) and the electron beam (homogeneous electron beam density \(n_{0b} = 10^{-4}n_0\)) are co-propagating through the plasma at \(\theta = 10^\circ\), where \(\theta\) is the angle between the direction of beam propagation and plasma density modulation.

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However, this is a two-stage process, in which the beam must be density modulated and then bent. We have proposed a single-stage mechanism for generating such electron beams. An electron beam co-propagating with a laser through an obliquely modulated plasma can excite oblique modulation on the electron beam. As well as taking place in a single stage, this method may also reduce the size of the system, and can provide flexibility in the choice of plasma modulation wavelength, \( \lambda_q \), which is almost fixed for a magnetic undulator.

In our scheme, an electron beam and an electromagnetic wave co-propagate through an obliquely density-modulated plasma. Resonant interactions take place between the electromagnetic wave, the plasma modulation, and the electron beam, and consequently the electron beam acquires an oblique static density modulation. The beam modulation period, \( \lambda_q + \), depends on the wavelength of the electromagnetic wave \( \lambda \), the plasma modulation period, \( \lambda_q \), and the beam velocity, \( v_0 \). The value of \( \lambda_q \) required for the resonance can range from few microns to a few millimeters. As the plasma density increases, the required \( \lambda_q \) decreases, but it increases with the beam relativistic factor \( \gamma_{0b} \), saturating for \( \gamma_{0b} \geq 4 \) and plasma densities \( n_0 \geq 6 \times 10^{13}\text{cm}^{-3} \) (see Figure 1).

To understand and demonstrate the resonance mechanism, we supplemented our derived equations with particle-in-cell (PIC) simulations we carried out using OSIRIS, which is a fully parallelized, fully implicit, fully relativistic, and fully object-oriented PIC code for modeling intense beam plasma interactions.

We used a \( 500 \times 100c/\omega_p \) simulation box, resolved with 5000 cells in the \( z \)- (parallel to the beam propagation), and with 500 cells in the \( x \)- (perpendicular to the beam propagation) directions, where \( c/\omega_p \) is the skin depth of the plasma, \( c \) is the light velocity in a vacuum, and \( \omega_p \) is the plasma frequency. We considered plasma electrons and beam electrons as two different species, with plasma electron specifications of plasma density modulation amplitude \( n_q = 0.6n_0 \), \( \lambda_q = 8.81c/\omega_p \), and \( \theta = 20^\circ \), where \( \theta \) is the angle between the direction of beam propagation and plasma density modulation. Beam electron specifications were bunch length \( 50c/\omega_p \), width \( 20c/\omega_p \), and beam density \( n_{0b} = 10^{-4}n_0 \), propagating along the \( z \) direction with \( \gamma_{0b} = 2 \).

We used nine particles per cell for both the species in the simulations. We initialized an electromagnetic wave with transverse gaussian profile with the following parameters: normalized vector potential \( \tilde{a}_0 = 0.005 \) (normalization factor: \( mc^2/\epsilon \), where \( \epsilon \) and \( m \) are the charge and rest mass of the electron, respectively); laser frequency \( \lambda = 1.88c/\omega_p \); spot size \( 20c/\omega_p \); and full longitudinal pulse length \( 100c/\omega_p \). The plasma covers the full box from \( z = 100c/\omega_p \) to \( z = 500c/\omega_p \), with the ions forming an immobile neutralizing fluid background. 2D simulation results showed that the density modulation in the electron beam is due to the resonant interaction between the electron beam, plasma, and the electromagnetic wave (see Figure 2). We observed well-defined modulation structures in the beam density, with

![Figure 2. Density modulation of the electron beam showing the beam electron distribution in the x-z plane, with the beam propagating in z-direction (a). Density modulation of the electron beam along the axis at \( x = 50c/\omega_p \), where \( c/\omega_p \) is the skin depth of the plasma, \( c \) is the speed of light in a vacuum, and \( \omega_p \) is the plasma frequency and equal to \( 5.64 \times 10^4n_0[\text{cm}^{-3}]^{1/2}\text{rad/sec} \) (b). Fourier transform of beam density plotting the beam mode \( k_+ \) distribution, where \( k_+ = 2\pi/\lambda_q + \) and \( \lambda_q + \) is the beam modulation period (c). The Fourier distribution of beam density (d). \( k_+ \): The x and z components of \( k_+ \), respectively. \( n_b \): Beam electron density. FFT: Fast Fourier transform.](image)

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a finite transverse component—see Figure 2(a) and (b)—at matched parameters with \( k_{+z} = 3.79 \omega_p/c \) and \( k_{+x} = 0.67 \omega_p/c \), where \( k_{+x} \) and \( k_{+z} \) are the \( x \)- and \( z \)-components of \( k_+ \), respectively: see Figure 2(c) and (d). In the absence of the electromagnetic wave, we observed no density modulation on the electron beam, which confirms that the formation of the density modulation results from the resonant interaction between the electron beam, plasma, and the electromagnetic wave.

In summary, we have shown by computer simulations that an oblique modulation in the electron beam density\(^{10}\) can be obtained by co-propagating the beam with an electromagnetic wave through a modulated plasma, without using any magnetic undulator.\(^{10}\) This novel mechanism has the potential to generate compact, tunable THz radiation sources. The next step will be to examine whether we can obtain obliquely modulated electron beams using modulated lasers, and to study the beams’ radiation signature.

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**Author Information**

V. B. Pathak, R. A. Fonseca, and L. O. Silva
Plasma and Laser Group
and
Institute for Plasmas and Nuclear Fusion
Institute of Advanced Technology
Lisbon, Portugal

Vishwa Pathak is a postdoctoral fellow with a PhD in physics from the Indian Institute of Technology Delhi. His area of interest is plasma-based wakefield accelerators, parametric instabilities, and radiation generation

V. K. Tripathi
Physics Department
Indian Institute of Technology Delhi
New Delhi, India

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