Generation of high power sub millimeter radiation using free electron laser

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Abstract. We have developed an analytical formalism to study the emission of high power radiation lying in the sub millimetre range. A relativistic electron beam (REB) is velocity modulated by the pondermotive force exerted by the laser beams. After passing through the drift space, the beam gets density modulated which further interacts with the strong field wiggler and acquires a transverse velocity that couples with the modulated density of the beam in the presence of ion channel which contribute to the non-linear current density which further leads to the emission of the radiation. The output radiation can be modified by changing the wiggler parameters and the energy of the electron beam. The power of the output radiation is found to increase with the modulation. The obtained radiation can be employed for various applications.

1. Introduction
The emission of high power terahertz (sub millimetre) radiation has attained a great interest in the field of research due to its potential applications including spectroscopy, remote sensing, biomedical, communication and security imaging [1-4]. THz waves are preferred over microwaves for broadband mobile communications and local area network due to their high frequency and more bandwidth [5]. A modulated electron beam is an efficient source for the generation of radiation using free electron laser as a high frequency device [6-7]. Xiang et al [8] have studied experimentally the generation of terahertz radiation using electron beam, modulated by the down conversion of the frequency of optical lasers and observed that the radiation can be altered by the by varying the lasers frequency and the electron beam energy. Bhasin and Sharma [9] have employed an energy modulated electron beam in a dielectric loaded waveguide in the presence of external magnetic field. They observed that the gain and efficiency of the radiation increases with the modulation and the growth rate decreases monotonically with the radiation frequency. Ion channel acts as guiding medium for the electron beam. The emission of terahertz radiation using helical wiggler in the presence of ion channel has been studied by Hasanbeigi et al [10]. They concluded that the power of the output radiation increases with the ion density, energy and radius of the electron beam.

In this paper, we have analysed the power of the output terahertz radiation, emitted by the interaction of a density modulated relativistic electron beam with an electromagnetic wave wiggler in the presence of an ion channel.
2. Physical Model

We consider two laser beams which employ a pondermotive force on interacting with the REB which leads to velocity modulation of the beam. When this beam further travels through the drift space, the current modulation converts into density modulation. This mechanism of premodulation is similar to that of klystron [11]. The modulated beam density \( n_{mb} \) [12] is obtained as

\[
n_{mb} = -2n_0 J_1 \left( \frac{\omega_b \rho \xi}{\nu_b} \right) \cos \left( \omega_b \tau - \phi \right),
\]

where \( n_0 \) is the initial beam density, \( \nu_b \) is the initial velocity of the beam, \( \omega_b \) is the frequency difference of two lasers in terahertz range, \( \rho \) is the length of drift space,

\[
\xi = \frac{k_b \rho c^2 e A_I}{2 \nu_b^2} \frac{e A_H^*}{\omega_H c} \sin(\varphi),
\]

where \( \varphi = \frac{(\omega_b - k_b \nu_b) \rho}{2 \nu_b} \) is the phase angle of the modulation, \( k_b \) is the beam wave vector, \( A_I, A_H \) and \( \omega_I, \omega_H \) are the amplitudes of electric field and frequencies of two laser beams, respectively.

![Figure 1: Interaction of laser modulated REB with the electromagnetic pump wave in the presence of ion channel.](image)

Further we consider the propagation of modulated REB in the field of the electromagnetic wave and the uniform density ion channel. The modulated REB acquires normalized oscillatory velocity \( \vec{\beta}_{bw} \) due to the pump wave and the ion channel field.

\[
\vec{\beta}_{bw} = \frac{\Omega_0 (\beta_b + \beta_0)^2}{\alpha c^2 - (\beta_b + \beta_0)^2} \cos(k_0 z + \omega_I t),
\]

where \( \Omega_0 = \frac{e B_0}{\gamma_0 mc^2 k_0} \) is the normalized frequency of wigglers, \( B_0 \) is the wigglers magnetic field, \( (\omega_0, k_0) \) is the frequency and wave vector of the wigglers wave respectively, \( \beta_b \) is the normalized beam velocity \( \omega_v = \left( \frac{2 \pi e^2 n_+}{\gamma_0 m_+ c^2} \right)^{1/2} \) is the normalized frequency of ion channel, \( n_+ \) is the ion density, \( m_+ \) is the mass of ions.

This oscillatory velocity couples with the modulated beam density to give non-linear current density. The magnetic field of the terahertz wave calculated using vector potential helps in evaluating the average power \( 4 \pi r^2 S_{av}, S_{av} = \frac{c}{2 \rho_0} |\vec{B}|^2 \) is the average Pouynting vector of the radiation.
Average power: 

\[ \text{Average power} = \frac{\pi c \mu_0 e^2 n_B^2 \Omega_0^2 \Omega_1^2 (\beta_b + \beta_0)^4}{2 \omega_c^2 - (\omega_c + \beta_0)^2} \mathcal{J}_1^2 \left( \frac{\omega_c \rho_b^2}{\nu_b} \right) \]  

(3)

where \( l_b \) is the electron bunch length, \( r_0 \) is the size of electron beam, \( \omega_1 \) is radiation frequency.

3. Results and Discussion

Typical parameters used for calculation are: \( v_b = 0.95c \), \( \gamma_0 = 3.2 \), \( n_b = 4 \times 10^{14} \text{ cm}^{-3} \), \( \rho = 500 \mu\text{m} \).

\[ l_b = 0.3cm, \quad \frac{eA_I}{m\omega_I} = 0.05, \quad \frac{eA_{II}}{m\omega_{II}} = 0.05. \]

Figure 2: The figure shows the variation of output average power \((4\pi r^2 S_{av})\) with radiation frequency \((\omega_1)\) and ion channel frequency \((\omega_c)\).

Figure 3: The figure shows the variation of output power \((4\pi r^2 S_{av})\) with radiation frequency \((\omega_1)\) and pump field amplitude \((B_0)\).
From figure 2, it can be seen that the average output power of the radiation for a fixed value of ion density, increases with the radiation frequency up to a certain maximum value and then decreases and further repeats the pattern. This pattern is followed by the Bessel’s function which appears due to the modulation of the electron beam density. The power also increases with the frequency of the ion channel. From figure 3, it is observed that the output power increases with the amplitude of magnetic field of the pump wave. It also increases with the radiation frequency and shows Bessel’s function character.

Figure 4: The figure illustrates the variation of output average power with the radiation frequency for different beam densities.

It can be inferred from figure 4 that the output average power of the radiation wave increases with the increase of density of the electron beam as more the number of electrons will be available to transfer their energy to the radiation wave. Further, it increases initially with the output frequency, attains a maximum value at a point where resonance occurs and then starts decreasing.

4. Conclusion
The terahertz radiation emitted using a density modulated beam with the effects of ion channel can be modified by varying the parameters of electron beam, amplitude of the pump field and frequency of the ion channel. Increase in ion channel density helps in enhancement of the output power. The modulation of the beam is affected by the parameters of the laser beams and the electron beam. The power scales as square of the electron beam density and the amplitude of the pump wiggler field. The tuned radiation thus obtained can be used for future practical applications.

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