BEAT-WAVE LASER-DRIVEN PHOTOINJECTOR FOR SUPERRADIANCE FREE-ELECTRON LASER

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Abstract

A periodically bunched electron beam is useful for generating electron superradiance. This paper studies the generation and acceleration of density-modulated electron beams from a photocathode electron gun driven by a laser beat wave. Computer simulation shows feasibility of accelerating and preserving the density-modulated electron beam in an accelerator.

INTRODUCTION

Radiation from relativistic electrons is important for generating THz and *x*-ray wavelengths at which solid-state laser sources are not readily available. The spectral brightness of electron radiation is strongly influenced by the electron bunch length relative to the radiation wavelength. When the electron bunch length is significantly shorter than the radiation wavelength, the radiation fields from all electrons are coherent and can be summed to a large value.

In a conventional free-electron laser (FEL) the optical feedbacks from resonator mirrors can help the electron bunching process during laser buildup. At short wavelengths a single-pass, mirrorless FEL generating self-amplified spontaneous emission (SASE) is the preferred mode of operation due to the scarce of mirror materials at deep UV and *x*-ray wavelengths. However, it usually takes a long undulator for a high-quality electron beam to form micro-bunches and reach the onset of the SASE mode. It is therefore desirable to invent an accelerator that generates a periodically bunched electron beam with an arbitrarily tunable bunch length and bunch frequency. Perviously Neumann *et al.* [1] used a comb filter to induce a few temporal ripples to the driver laser of a photocathode gun and observed coherently enhanced radiation at THz. In the paper, a laser beat wave with a tunable beat frequency is employed to induce a density-modulated photocurrent from the photocathode cathode of an electron gun. We study in this paper the acceleration of the density-modulated electron beam and the implementation of such a beat-wave laser system.

SUPERRADIANCE

Superradiance from relativistic electrons has been studied theoretically and experimentally in numerous papers. To facilitate subsequent discussions, we briefly review a few key concepts of superradiance based on Gover's work [2].

Regardless of the nature of the radiation device or scheme, let $(dW/d\omega)_1$ denote the spectral energy emitted from a single electron, where W is the radiation energy, ω is the angular frequency of the radiation, and subscript 1 denotes "a single electron". When a long stream of N electrons traverses a radiation device, the electrons radiate with all possible phases between 0 and 2π and the radiation has a spectral energy expressed by

$$(dW/d\omega)_{inc} = N(dW/d\omega)_1 \, , \qquad (1)$$

Eq. (1) is linearly proportional to the total number of electrons participating in the radiation process, because not all the radiation fields from the electrons are added up constructively. However, if N_b electrons are distributed in an infinitesimal time period, all the radiation fields from the electrons are in phase and summed up constructively, resulting in a total spectral energy equal to $N_b^2(dW/d\omega)_1$. This radiation process is dubbed as superradiant emission or superradiance. To account for a finite electron bunch length τ_b the total energy spectral density from an electron bunch is expressed by

$$(dW/d\omega)_{SR} = N_b^2(dW/d\omega)_1 M_b^2(\omega)\, , \qquad (2)$$

where $M_b(\omega)$ is the Fourier transform of the electron pulse-shape function with a unitary peak amplitude. Usually $M_b^2(\omega)$ has a characteristic width ~$1/\tau_b$ in the frequency domain. If there are N_{pb} electron "micro-bunches" repeating at a rate $\omega_{pb}/2\pi$ and there are N_b electrons in each micro-bunch, the total spectral energy from such an electron beam becomes

$$(dW/d\omega)_{SR,pb} = N_b^2 N_{pb}^2 (dW/d\omega)_1 M_b^2(\omega) M_{pb}^2(\omega)\, , \qquad (3)$$

where

$$M_{pb}^2(\omega) = \frac{\sin^2(N_{pb}\pi\omega/\omega_{pb})}{N_{pb}^2 \sin^2(\pi\omega/\omega_{pb})} \qquad (4)$$

is the coherent sum of the radiation fields from all the micro-bunches and has a unitary amplitude at the resonance frequencies (m = 1, 2, 3…). At $\omega = \omega_{pb}$, the spectral energy, Eq. (3), is enhanced by a factor equal to the number of electrons compared with that from an unbunched beam. Superradiance power has a quadratic dependence on a beam current, as can be seen from Eq. (2, 3); whereas the incoherent radiation power from a long-bunch beam is linearly proportional to a beam current, according to Eq. (1).

In Eq. (1), the spectral linewidth of the radiation from a long electron bunch is determined by the radiation bandwidth of a radiation device or a radiation scheme.

The superradiance linewidth from a short electron bunch, according to Eq. (2), is further modulated by $M_b^2(\omega)$. For a short electron bunch, $M_b^2(\omega)$ is usually a broadband curve. The coherent sum Eq. (4), however, has narrow spectral peaks at the frequencies $\omega = m\omega_{pb}$. Each resonant peak has a linewidth of ω_{pb}/N_{pb}. The superradiance linewidth from periodically bunched electrons can be greatly reduced for a large N_{pb}.

GENERATION OF LASER BEAT-WAVE BUNCHED BEAM

We illustrate in Fig. 1 the schematic of the proposed beat-wave bunched beam technique for producing and accelerating periodically bunched electrons with a variable bunch frequency. The idea is to use a laser beat wave to induce periodically density-modulated photoemission from the photocathode of an electron gun. The density-modulated photocurrent is then accelerated to some energy for generating superradiance in a downstream radiation device. The beat-wave laser system consists of wavelength-tunable lasers for generating laser beat waves with a variable beat frequency. If the desired electron bunch frequency is higher than the beat frequency available from a laser beat wave, one could in principle first generate an energy-chirped, density-modulated beam and compress it in a magnetic compressor to obtain a beam with a higher bunch frequency.

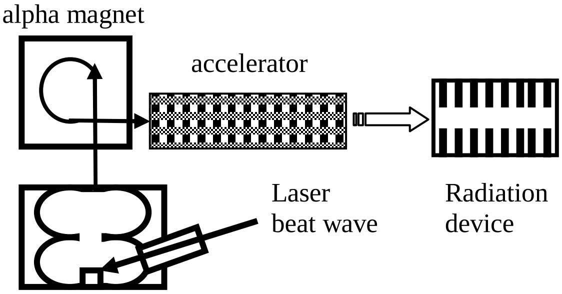

Figure 1: A laser beat wave excites a density-modulated photocurrent from a photocathode, which is subsequently accelerated to some energy for generating superradiance in a radiation device. An alpha magnetic could compress a density-modulated, energy-chirped beam to obtain a beam with a higher bunch frequency.

A laser beat wave can be generated from a superposition of two laser fields with a constant frequency offset. Assume that a beat-wave field is generated from the sum of two equal-amplitude laser fields with a frequency offset $\Delta\omega$. The instantaneous intensity of the beat wave is given by

$$I_{ins} = 4I_0 \cos^2[(\omega + \frac{\Delta\omega}{2})t] \cdot \cos^2(\frac{\Delta\omega}{2}t), \qquad (5)$$

where t is the time variable, I_0 is the average intensity of each laser component, and $\omega+\Delta\omega/2$ is the central frequency of the laser beat wave. A laser beat wave can also be generated from a superposition of several laser fields with a constant frequency shift $\Delta\omega$. For example, the coherent sum of the N_l equal-amplitude laser fields gives a time-averaged intensity

$$I_{avg} = N_l^2 I_0 \frac{\sin^2 \frac{N_l \Delta\omega}{2} t}{N_l^2 \sin^2 \frac{\Delta\omega}{2} t}. \qquad (6)$$

Eq. (6) shows laser beat pulses repeating at a frequency $\Delta\omega$ with a pulse width equal to $(2\pi/\Delta\omega)/N_l$. The beat pulses given in Eq. (6) are very useful for providing high-contrast density modulation to the photocurrent from a photocathode. By adjusting the number of interfering waves N_l one can adjust the beat-pulse width to optimize the modulation depth of the photocurrent emitted from a photocathode. In fact the locked-locked laser pulse commonly used for exciting a photocathode gun is a consequence of beating many longitudinal modes in a laser cavity with a beat frequency of ~100 MHz. To obtain a narrow beat pulse repeating at THz, one could, for example, use an intense laser to pump a Raman material with a THz Stokes shift and generate multiple Stokes waves beating at the Stoke shift. Of course, the shortest electron bunch that can be generated from photoemission depends on the temporal response of a specific cathode material. In view of the mechanism of a photoemission process, it is also preferred that all the beat-wave photons have photon energy higher than the work function of a cathode material.

ACCELERATION OF PERIODICALLY BUNCHED ELECTRONS

A major concern for the proposed bunching technology is whether particle acceleration following the density-modulated photoemission would smear out the periodic electron micro-bunches. In the following we conduct a feasibility study for accelerating ps and fs micro-bunches by using a space-charge tracking code ASTRA [3].

We first simulated the particle acceleration for the 1-1/2 cell SSRL electron gun [4] with twenty-five Gaussian electron bunches with 1-fs rms bunch length periodically emitted over 250-fs duration from the photocathode. The emitted charges have a uniform radial distribution on a 3-mm diameter cathode. Each micro-electron bunch contains 1 pC in a 10-fs time period. The total 25 pC charge was evenly divided into 12500 negatively charged macro-particles. The average current over the whole 250 fs duration is 100 A. With a peak acceleration field of 125 MV/m in the 2nd gun cell and an acceleration phase of 211.6°, Fig. 2 shows periodic density modulation of a 4-MeV beam with a characteristic period of 6 μm along the axial distance (z_e) at the gun exit. The output pulse duration is stretched to 500 fs and thus the average beam current is reduced to 50 A. Since the 250-fs emission time only occupies a very small RF acceleration phase, we confirm in the ASTRA simulation that the space charge field is responsible for the pulse-length increase. Although the shortest possible electron bunch is limited by a cathode material, the above computer stimulation is just an illustration of preserving periodic fs electron bunches during particle acceleration. Whether generation of fs electron bunches from a certain cathode mateiral is practical or not, it is another subject of study in the future.

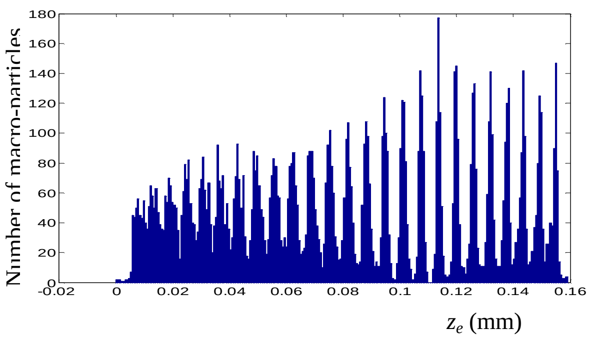

Figure 2: Histogram of the 4-MeV charges versus z at the exit of the SSRL gun with an input beam of twenty-five Gaussian bunches periodically emitted over 250 fs. The output beam distribution shows a good contrast in the density modulation.

A Smith-Purcell emitter driven by a keV, mA electron gun usually generates negligible radiation at THz. This proposed technique could be very useful for producing coherent radiation at THz frequencies from a miniature Smith-Purcell free-electron laser. Previously Ref. [5] reported Smith-Purcell superradiance, which was interpreted by Ref. [6] as coherent radiation from surface-mode induced electron bunching at the sub-harmonic of the Smith-Purcell radiation frequency. Up to date, no independent experiment can verify the superradiance claimed by Ref. [5]. A convenient approach is to produce electron bunches repeating at the radiation frequency directly from an electron source and generate wavelength tunable superradiance from a Smith-Purcell radiator. In our simulation, we emitted 50 Gaussian electron bunches each having a 0.2-ps rms bunch length from the photocathode of a 42 keV DC accelerator over a 50-ps time period. Each electron bunch contains 1 fC charge or 6.25×10^3 electrons, resulting 1 mA average current over the 50 ps macropulse. The electrons have a uniform radial distribution on the cathode with an rms radius of 0.3 mm. The electron gun has a length of 4.5 cm with 1-Tesla axial magnetic field for beam confinement. Figures 3(a) and (b) are the $M_b^2(\omega)M_{pb}^2(\omega)$ for the emitted electrons and the 42-keV output electrons, respectively. The accelerated electrons are slightly re-distributed due to the space charge force. Nonetheless the enhancement in the spectral power due to the periodic bunching is apparent at the harmonics of the bunching frequencies. For example, with 6.25×10^3 electrons/bunch and 1000 bunches over a 1 ns time, the spectral energy is coherently enhanced by almost 7 orders of magnitude at 1 THz.

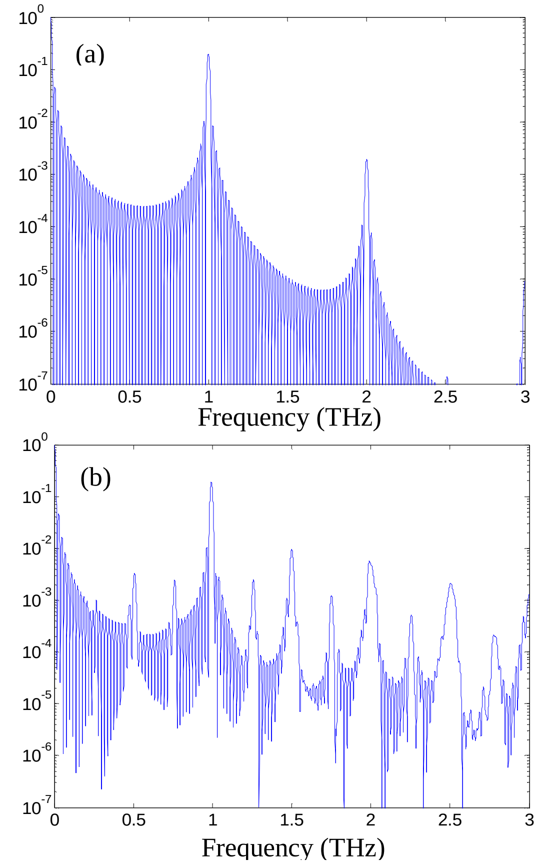

Figure 3: The $[M_b(\omega)M_{pb}(\omega)]^2$ of 50 electron bunches repeating at 1 THz (a) before and (b) after acceleration in a 40 keV DC electron gun. Spectral enhancement at the harmonics of 1 THz frequency is apparent.

FREQUENCY-TUNABLE BEAT-WAVE LASER SYSTEM

Although the laser beat wave can simply be obtained by overlapping two chirped pulses from the laser driver of a photocathode gun, the intensity contrast in the beat wave and the tunability in the beat frequency are not ideal [7]. We describe below one example of engineering a beat-wave UV laser system capable of generating mJ-level, 10-ps laser pulses near 260 nm with a tunable beat frequency range over 200 THz. Figure 4 shows the block diagram of the proposed beat-wave laser system, which consists of three major stages with a beat-wave seed source, a first-stage broadband pulsed amplifier and a second harmonic generator, and finally a frequency-tripled Ti:sapphire laser amplifier. The two seed lasers in the first stage are often used in optical communications. The Ti:sapphire laser amplifier and harmonic generators are commonly seen for driving a Cu photocathode gun. Specifically, one can starts with the beating of kHz-linewidth distributed-feedback (DFB) and frequency-tunable external-cavity diode lasers (ECDL) near the optical-communication wavelength 1.5 μm. An Erbium-doped fiber amplifier (EDFA) following the DFB diode laser and ECDL boosts the beat-note power to ~100 mW. The CW beat signal can be further amplified in a pulsed optical parametric amplifier (OPA) pumped by, say, a diode-pumped mode-locked Nd:YVO_4 laser to generate ~10-ps beat-wave pulses with nJ pulse energy. After frequency doubling the beat-wave pulses in a second harmonic generator (SHG), the wavelengths of the beat wave will fall into the bandwidth of a Ti:sapphire amplifier. Therefore, the rest of the laser system can be a replication of the UV laser amplifier for driving a Cu photocathode gun. The proposed beat-wave laser system spares a mode-locked Ti:sapphire laser oscillator from a typical photocathode-gun laser driver. Instead, a user-friendly, directly diode-pumped mode-locked Nd:YVO4 is proposed for pumping the OPA to generate beat-wave pulses near the optical-communication wavelengths.

To produce the proposed Smith-Purcell superradiance, the mode-locked Nd laser can be replaced by an economic Q-switched Nd laser, and harmonic generators can directly follow the OPA to generate long-pulse UV laser.

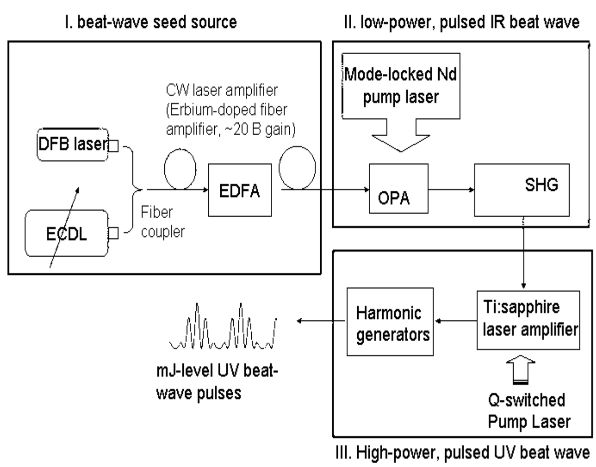

Figure 4: One example of a beat-wave laser system modified from a typical UV laser system for a Cu-photocathode gun.

The beat frequency of the laser system can be arbitrarily tuned by adjusting the wavelength of the ECDL or by plugging in assorted narrow-line telecommunication diode lasers with a wavelength range between 1.3 and 1.6 μm. Taking into account the successive harmonic generations leading to the 260 nm photons, one would expect a beat-frequency tuning range well over 240 THz.

SUMMARY

We have described a novel scheme for generating tunable periodic electron bunches for superradiance FEL. Specifically a laser beat wave is used to introduce density modulation to the photocurrent of a photocathode electron gun. The periodic electron bunches are subsequently accelerated to high energy in a particle accelerator. Computer simulations using the space-charge tracking code, ASTRA, showed feasibility of accelerating and preserving the density-modulated electron beam at both nonrelativistic and relativistic energies.

We have also described the implementation of a beat-wave laser system with a beat-frequency tuning range over 200 THz. The laser system adopts the state-of-the-art and yet economic photonics products often used in the optical-communication and laser industries. Real-time tuning on the beat frequency provides unprecedented flexibility to match the frequency of down-stream radiation devices.

The shortest electron-bunch length from the proposed beat-wave bunching technique could be limited by the beat-wave frequency or the response time of a cathode material. We proposed chirped-pulse compression in an alpha magnet to increase the bunch frequency. Knowing the potential problem of microbunching instability in the compression, we have planned a feasibility study in the near future.

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