GAIN AND COHERENCE ENHANCEMENT OF SASE FEL USING LASER-PREBUNCHED ELECTRONS

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Abstract

We conduct a simulation study on the acceleration of periodically loaded electrons in a 6-MeV photocathode electron gun driven by a laser beat wave with a beat frequency of 4.35 THz. The density modulation of the electrons is well preserved during particle acceleration. The periodically bunched electrons are then injected into a single-pass free-electron laser to quickly generate a few tens of kW electron superradiance at 63.5 μm.

INTRODUCTION

It is well known that, if the electron bunch length is significantly shorter than the radiation wavelength, the spectral power of the electron radiation is proportional to the square of the electron current or to the square of the total number of electrons participating in the radiation process. This coherent radiation is dubbed as electron superradiance.

To facilitate the discussion, we briefly describe in the following the theory of electron superradiance based on Gover's formulation [1]. In general, the spectral energy of the radiation from an electron bunch with a bunch length τ_b and an electron number N_b is expressed by the equation

$$\left(dW/d\omega\right)_{SR} = N_b^2 \left(dW/d\omega\right)_1 M_b^2(\omega)\,, \tag{1}$$

where $(dW/d\omega)_1$ denotes the spectral energy emitted from a single electron with W being the radiation energy and ω being the angular frequency of the radiation, $M_b(\omega)$ is the Fourier transform of the electron pulse-shape function with a unitary peak amplitude. If the radiating electron beam contains N_{pb} such electron bunches repeating at a rate $\omega_{pb}/2\pi$, the total radiated spectral energy becomes

$$\begin{aligned}&\left(dW/d\omega\right)_{SR,pb} = \\ &N_b^2 N_{pb}^2 \left(dW/d\omega\right)_1 M_b^2(\omega) M_{pb}^2(\omega)\end{aligned}\,, \tag{2}$$

where

$$M_{pb}^2(\omega) = \frac{\sin^2(N_{pb}\pi\omega/\omega_{pb})}{N_{pb}^2 \sin^2(\pi\omega/\omega_{pb})}\,, \tag{3}$$

is the coherent sum of the radiation fields from all the micro-bunches and has a unitary peak amplitude at the frequencies $\omega = m\omega_{pb}$ (m = 1, 2, 3…). For a short electron bunch, $M_b^2(\omega)$ is usually a broad-band function. The spectral linewidth of $M_{pb}^2(\omega)$ at $\omega = m\omega_{pb}$ is given by $\sim \omega_{pb}/N_{pb}$, which, for a large number of periodic electron bunches, could be much narrower than the intrinsic spectral linewidth of a radiation device governed by $\left(dW/d\omega\right)_1$. Therefore, a self-amplified spontaneous emission (SASE) free-electron laser (FEL) is expected to have enhanced gain and coherence when driven by a periodically bunched electron beam. Since electrons are discrete particles, the term $M_b(\omega)M_{pb}(\omega)$, describing the degree of electron bunching at the frequency ω, is sometimes called the electron bunching factor.

Previously we have proposed the use of a laser beat wave to excite periodic emissions of electrons from the photocathode of an electron accelerator [2]. In this paper, we study a THz single-pass FEL driven by such a laser-beat-wave (Labew) photocathode accelerator. The system configuration of this study is depicted in Fig. 1, consisting of two major components, a RF photocathode gun and a solenoid-derived wiggler. The periodically bunched electrons are excited by a laser beat wave at the cathode, accelerated by a 1.6-cell S-band accelerator, and directly injected into a solenoid-derived wiggler to generate the electron superradiance.

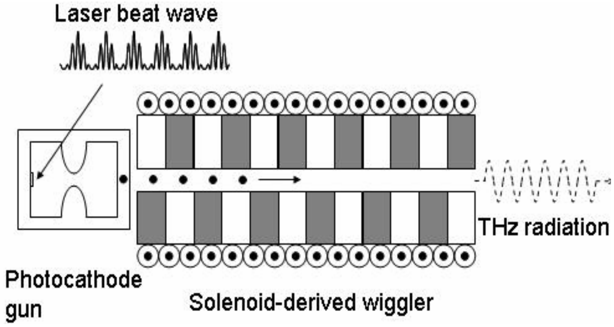

Figure 1: The system configuration for studying a THz superradiance FEL driven by a Labew photocathode gun.

Labew PHOTOCATHODE GUN

In this section, we study the acceleration of periodically bunched electrons in the BNL/UCLA/SLAC 1.6-cell S-band photocathode electron gun [3] by using the space charge tracking code ASTRA [4]. We operate the gun at a peak acceleration gradient of 140 MV/m. The electrons are emitted from the photocathode with a radial distribution within a 0.75-mm rms radius. For the first case in our simulation, we emitted a total of 1-nC electrons uniformly distributed over 10-ps duration. For the second case in our simulation, we equally divided the

1-nC charges into 44 micro-bunches over the same 10 ps duration. The micro-bunch separation is set to be six sigma of the Gaussian bunch length. For both cases, 14080 macro-particles were used in the simulations. The output beam parameters for the two cases are listed in Table 1. Although the essential beam parameters of the macro pulses at the gun exit are nearly identical for both cases, the longitudinal micro-structures of the electrons for the two cases are very different. Figures 2(a) and (b) show a comparison between the longitudinal distributions of the accelerated single electron bunch and the accelerated periodic electron bunches, respectively. The longitudinal distribution of the single-bunch beam remains more or less uniform after acceleration, whereas that of the periodically bunched beam shows redistribution of electrons after acceleration. Although the leading part of the periodically loaded beam retains periodic bunching, the trailing part has no apparent bunching features. The particle redistribution is due to both the space charge field and the acceleration field during the acceleration process.

Table 1. Output beam characteristics for single-bunch acceleration and periodic-bunch acceleration. The two sets of parameters are nearly identical.

	rms beam energy	rms energy spread	rms emittance	rms beam radius
Single-bunch acceleration	6.3 MeV	3.6%	2.8 π-mm-mrad	1.3 mm
Periodic bunch acceleration	6.3 MeV	3.9%	2.6 π-mm-mrad	1.3 mm

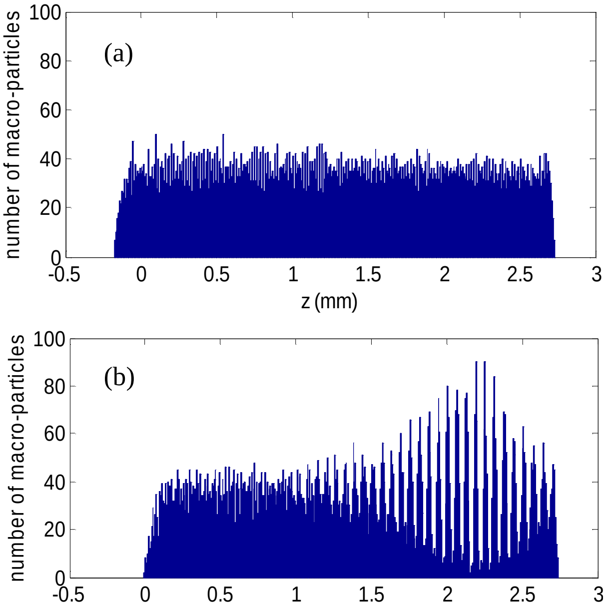

Figure 2: The electron distributions at the exit of the photocathode gun (a) for single-bunch acceleration and (b) for periodic-bunching acceleration.

The degree of electron bunching can be better described from the magnitude of the bunching factor $|M_b(\omega)M_{pb}(\omega)|$. We plot is Figure 3 the values of $|M_b(\omega)M_{pb}(\omega)|$ versus frequency before and after the acceleration of the periodically loaded beam. It is seen in Fig. 3(a) that the periodic bunches are nicely loaded at 4.35 THz at the cathode. In Fig. 3(b), the redistribution of the particles at the gun output causes some frequency broadening and magnitude reduction to the bunching factor. The fundamental frequency of the peak bunching is also shifted from 4.35 THz to 4.72 THz. Nevertheless the bunching factor is slightly reduced from 0.6 to 0.2 at the fundamental bunching frequency. In the next section, we show the importance of this bunching factor when driving a THz superradiance FEL.

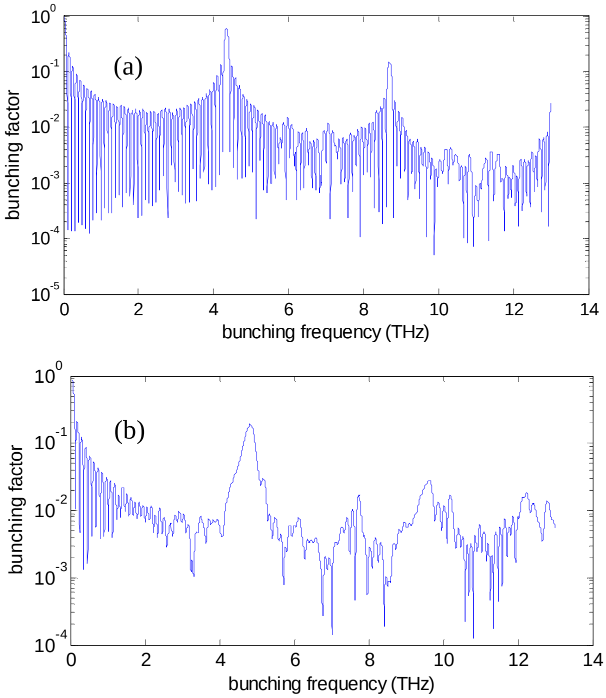

Figure 3: The bunching factor of the periodically loaded electron beam (a) before and (b) after acceleration in the photocathode gun. The space charge field and the acceleration field redistribute the electrons during acceleration and result in frequency broadening and magnitude reduction to the bunching factor.

SUPERRADIANCE FEL

The FEL wiggler in our choice for our simulation is a staggered-array solenoid-derived planar wiggler [5]. Among several advantages of using such a wiggler, the solenoid field is important for confining the low-energy electron beam. The system parameters chosen for our simulation study are: wiggler period = 1.5 cm, peak wiggler field = 7.2 kG., and solenoid field = 7.5 kG. For the 6.3 MeV driving beam, the synchronism wavelength of the FEL radiation is 63.5 μm.

We simulated the FEL power growth as a function of the wiggler length in the computer code GENESIS [6]. We use the Labew-gun beam parameters from ASTRA as the input beam parameters for the FEL simulation in GENESIS. To see the influence of the initial bunching, we varied the bunching factor when simulating the FEL performance. Figure 4 shows the FEL powers as a function of the wiggler length for initial bunching factors of 0, 10^{-8}, and 2×10^{-2}. To our surprise, the typical exponential growth of the (SASE FEL power is not seen in the range of our simulation study. With the zero bunching factor, the FEL gain is too low to build up the FEL power. However, for a strong initial bunching, the FEL power flats out at a high value almost immediately. This phenomenon suggests a strong superradiance process.

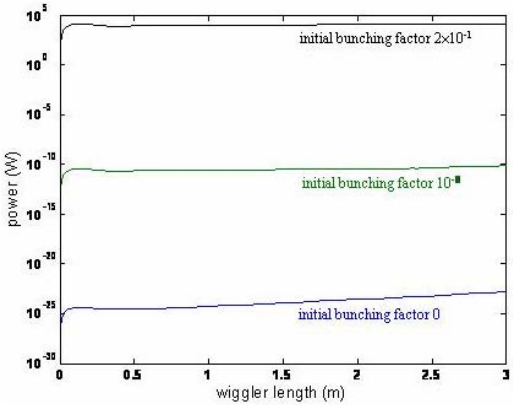

Figure 4: FEL power versus wiggler length with initial bunching factors = 0, 10^{-8}, and 0.2. With the 0.2 bunching factor, the FEL power quickly builds up to tens of kW.

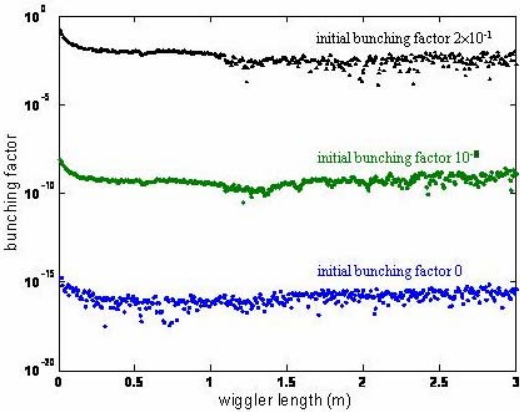

Figure 5: The variation of the bunching factors in the wiggler for the three initial bunching values, 0, 10^{-8}, and 2×10^{-2}. The space charge force in the low-energy beam tends to debunch the electrons.

Figure 5 shows the variation of the electron bunching factors in the wiggler for the three initial bunching values, 0, 10^{-8}, and 2×10^{-2}. It is interesting to see that the bunching factor does not increase over the wiggler length as usually seen in a SASE FEL, but tends to settle to a steady-state value despite of strong initial bunching. For example, the initial bunching factor 0.2 is reduced to about 10^{-3}, although the FEL power quickly reaches a few tens of kW. The steady-state bunching value is a result of the balance between the debunching force from the space charge field and the bunching force from the radiation field. The space-charge induced debunching becomes significant for a low energy beam and is not commonly seen for a short-wavelength SASE FEL. Without initial bunching, it is unlikely for the single-pass THz FEL power to grow to an appreciable value.

CONCLUSIONS

An single-pass FEL driven by laser-prebunched electrons can be a promising radiation source. We simulated the performance of a Labew photocathode gun. With 44 periodic Gaussian bunches loaded at the cathode over 10 ps, the bunching factor of the 6.3-MeV output beam is slightly reduced from an initial value of 0.6 to 0.2 at the fundamental bunching frequency. The debunching is a consequence of the redistribution of electrons under the space charge force and the acceleration force.

By using the beam parameters generated from the gun simulation, we simulated the performance of a single-pass FEL radiating at the fundamental bunching frequency of 4.72 THz. The laser pre-bunched beam promptly generates tens of kW radiation power in the single-pass FEL. This quick generation of the FEL power suggests the potential of implementing an ultra-compact FEL by using the Labew accelerator technology. Our study also shows that it is unlikely to build a single-pass FEL by using such a low-energy driving beam without initial bunching, because the strong space charge force prevents the electrons from forming micro-bunches.

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