

ULTRA-COMPACT MW THz SUPERRADIANCE FEL

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Abstract

I present a simulation study of a desktop, megawatt (MW), THz superradiance free-electron laser (FEL) driven by a THz-pulse-train photoinjector. With nominal electron parameters from a THz-pulse-train photoinjector, this superradiant FEL is capable of generating nearly 10-MW power at THz frequencies from a half-meter, single-pass undulator.

INTRODUCTION

THz radiation is of great interest in scientific and industrial applications. A free-electron laser (FEL) is the only THz radiation source capable of generating coherent THz radiation with both high average and peak powers. However, a free-electron laser is often criticized for its bulky size, high cost, and complex setup. I present in this paper a megawatt (MW)-peak-power, single-pass FEL with a greatly reduced size, cost, and complexity.

Electron bunching is the key mechanism for generating high-brightness radiation. When an electron bunch length is shorter than the radiation wavelength, the small radiation phase allows the radiation fields from all electrons to coherently add up to a large value. This phenomenon is called electron superradiance [1]. A long train of periodic electron bunches can further enhance the radiation brightness at harmonics of the bunching frequency. This radiation process is dubbed as comb-pulse superradiance in this paper. In the THz spectrum, there have been experimental demonstrations of electron superradiance from single [2] or few [3] pulses of electrons. The focus of this paper is to study THz comb-pulse superradiance from a long electron pulse train with a length much longer than the individual pulse length. In this regime, radiation amplification, in addition to the coherent spontaneous radiation, could be significant.

Without external seeding, it is difficult for a single-pass THz FEL operating in the self-amplified-spontaneous-emission mode [4,5] to reach saturation [6] due to the space-charge debunching force associated with a low energy electron beam. In recent years, there have been schemes employing fast laser pulses to induce the emission of THz electron pulses from a photoinjector [7-10]. As will be shown below, using a pre-formed electron pulse train at THz frequencies to drive the FEL can effectively solve this problem. Those schemes do not increase the length of a beam line and do not introduce energy spread to an electron beam, permitting the design of an ultra-compact electron radiation source at THz frequencies.

THZ-PULSE-TRAIN PHOTOINJECTOR

Figure 1 shows the schematic of the proposed superradiant FEL, wherein a short undulator is installed immediately after the emittance-compensating solenoid of a THz-pulse-train photoinjector. The fast electron pulse train is produced by illuminating the photocathode of the injector with a THz laser pulse train. The pre-bunched electron pulses generate comb-pulse superradiance in the undulator. The solenoid magnet is the only focusing element of the FEL.

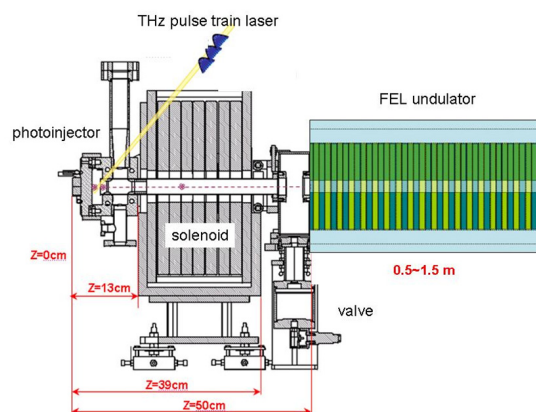


Figure 1. Schematic of the proposed ultra-compact superradiant FEL driven by a THz-pulse-train photoinjector. The pre-bunched electron pulses are injected into a helical undulator to generate electron superradiance. The emittance compensating solenoid is the only focusing element.

The acceleration process in a photoinjector could degrade the electron bunching. Therefore, I used the space-charge tracking code ASTRA [11] to simulate the acceleration of a comb- f beam at 2 THz propagating from the photocathode of a S-band 1.6-cell photoinjector to the FEL entrance at $z = 50$ cm. The peak acceleration field was set at 120 MV/m and the peak solenoid field was set at 3.15 kG to focus the beam at $z = 50$ cm. Since generating a transversely flattop, circular laser beam for a photoinjector is within reach of today's laser technology, I adopted a radial distribution of electrons at the cathode. Table I summarizes the input and output beam parameters for the photoinjector simulated by ASTRA. The fundamental bunching frequency is blue shifted to 2.4 THz due to the velocity bunching in a RF accelerator. The peak bunching factor is reduced from 0.85 at the cathode to 0.21 at the undulator entrance. However, if the amount of accelerated charges reduced to 0.1 nC, the bunching factor was found to be 0.4. Therefore, the space charge force has a profound influence on electron bunching.

Table 1. Summary of the input and output beam parameters at $z = 0$ and 50 cm with a 120-MV/m peak acceleration gradient in the photoinjector.

| Input Beam Parameters at $z = 0$ | | | | | | | |
|---------------------------------------|----------------------------------|---------------------------|----------------------|-----------------------------------|---------------------------|-------------------------|--|
| peak gradient | Charges | rms beam radius (mm) | σ_M | σ_t | micro-pulse rate | Bunching factor @ 2 THz | |
| 120 MV/m | 1 nC | 0.6 (radial distribution) | 4.25 ps (10-ps FWHM) | 50 fs | 2 THz | 0.85 | |
| Output Beam Parameters at $z = 50$ cm | | | | | | | |
| rms beam energy (γ) | rms energy spread $\Delta\gamma$ | rms beam radius (mm) | rms beam radius (mm) | rms emittance ($10^{-6} \pi$ -m) | bunching factor @ 2.4 THz | | |
| 11.9 | 7.4×10^{-2} | 6.3×10^{-2} | | 6.88 | 0.21 | | |

SUPERRADIANT FEL

The energy coupling among electrons, the slippage effect, the space-charge effect, and the electron-energy loss all affect the electron superradiant power from an undulator. In practice, the radiation field generated from trailing electrons could be amplified when slipping toward leading electrons. The amplification process is stopped when the electrons lose a significant amount of their kinetic energy to the radiation wave and fall off synchronization with the radiation field.

If the radiation frequency is chosen to be the fundamental bunching frequency at 2.4 THz according to Table I, it can be calculated from the FEL synchronism condition that the corresponding undulator period, peak undulator field, and undulator parameters are 18 mm, 8.3 kG, and, 0.98, respectively. By using the beam parameters in Table I and the helical undulator of our design, I continue to study the superradiant FEL by using the simulation code GENESIS [12]. Both ASTRA and GENESIS take into account the longitudinal space charge field, which is responsible for the dominant longitudinal plasma oscillation in the beam. Owing to the fast energy extraction from the electrons in a superradiant FEL, it is advantageous to adopt a tapered undulator to maintain the FEL synchronism condition over a longer distance. It is found from the simulation that the radiation power is maximized when the radiation frequency is red-shifted from 2.4 to 2.2 THz. This result suggests that the bunched electrons could continue to radiate into lower frequency components even after losing some energy. Figure 2(a) shows the FEL radiation power at 2.2 THz versus undulator length with 20% linear taper (blue curve) and without taper (green curve) in the undulator parameter between $z = 60$ and 150 cm. Without the taper, the FEL radiation power saturates at about 0.8 m in the undulator, reaching a power level of 10.7 MW; whereas with the taper, the power increases another 4 MW in the tapered section. Figure 2(b) shows the corresponding bunching factors versus distance in the two undulators. It is seen that the bunching factor first decreases due to the space charge force and then increases due to the fast build-up of the FEL power. If the driving beam was not initially

bunched to generate a strong enough radiation field to re-grab the electron bunches, this THz superradiant FEL would be otherwise impossible. In the tapered undulator, the bunching factor retains a nontrivial value between 60 and 150 cm in the undulator, which explains the continuous growth of the FEL power in that undulator section.

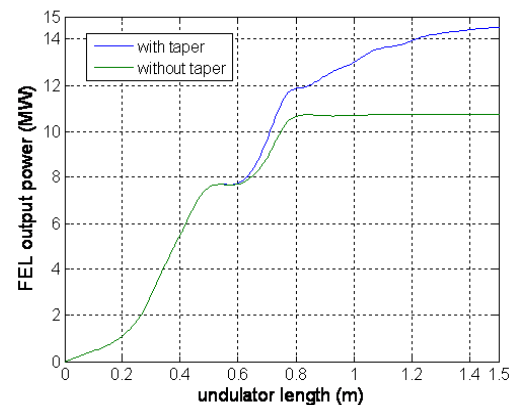


Fig. 2(a)

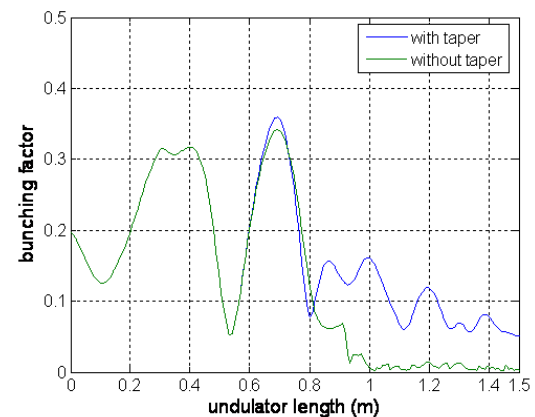


Fig. 2(b)

Figure 2: (a) The FEL radiation power at 2.2 THz with (blue curve) and without (green curve) tapering the undulator parameter. With 20% linear taper between 60 and 150 cm, the FEL radiation power increases by

another 4 MW. (b) The corresponding bunching factors versus distance for the two undulators. The bunching factor first decreases due to the space-charge debunching, but quickly shoots up to a higher value due to the fast buildup of the FEL power. The bunching factor retains a nontrivial value in the tapered section of the undulator.

It is seen from Fig. 2(b) that the bunching factor initially decreases to a value slightly over 0.1 and then shoots up to a higher one due to the fast build-up of the FEL power. Therefore, the FEL output power should not be greatly affected as long as the initial bunching is better than 10%. To show the dependence of the radiation power on the initial bunching factor, I plot in Fig. 3 the FEL power versus distance in the 20% tapered undulator for initial bunching factors of 0.01, 0.1, and 0.2. Apparently, a larger initial bunching factor helps build up the FEL power. Even with 1% bunching at the undulator entrance, the proposed superradiant FEL can produce MW-level radiation power.

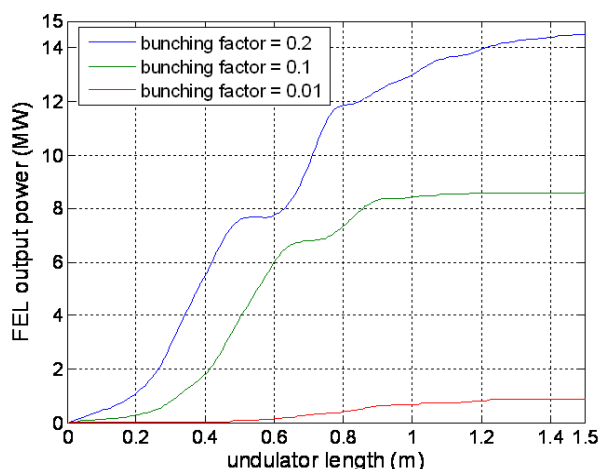


Figure 3: The effect of initial bunching factor on the FEL radiation power from the 20% tapered undulator. To obtain MW-level radiation power, the bunching factor should be higher than 1%.

CONCLUSIONS

In summary, I studied in this paper a superradiant FEL at THz frequencies and found an interesting regime of FEL operation, in which space charge debunching is overcome by radiation re-bunching when a low-energy electron pulse train is just injected into an undulator. With nominal beam parameters from a S-band THz-pulse-train photoinjector [13], I show in simulation that MW-level radiation power at THz frequencies is achievable from a single-pass undulator with a sub-meter length. The proposed THz superradiant FEL employs a short undulator directly attached to the emittance compensating coil of a MeV photoinjector of the electron gun without using any additional beam focusing elements. This compact design allows the construction of a MW FEL at THz frequencies on an ordinary desk. I also show that

tapering the undulator can further increase the radiation power by more than 35%. The spectral property of this FEL with and without external seeding is our next subject of study.

ACKNOWLEDGMENTS

This work is supported by National Science Council under Contract NSC 97-2112-M-007-018-MY2.

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