COMPACT THz RADIATION SOURCE BASED ON A PHOTOCATHODE RF GUN*

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Abstract

Our group has proposed a simple laser technology to generate a laser pulse sequence with a pulse repetition rate at the THz level and a micro-pulse width of several tens of femtosecond. The laser pulse sequence is used as the driving laser for a photocathode RF gun. The RF gun generates a pre-micro-bunched electron beam and immediately produces super-radiation in a short wiggler. In this paper we describe a handmade laser technology for a 16-pulse laser sequence. We present the results of a detailed simulation of the bunching factor with respect to the injection phase, the bunch charge, and the jitter of the time spacing and charge among the micro-bunches in the gun. Super-radiation is obtained from a 16-micro-bunch train with a 200pC bunch charge, and saturation can be achieved at a 150μm wavelength along a 0.4 meter length of the wiggler (radiation power 0.68MW, and energy 5.24μJ/pulse). The whole THz FEL facility can be scaled to the size of a tabletop.

INTRODUCTION

Terahertz radiation is formed by electromagnetic waves in the scientifically rich but technologically limited frequency range of 0.1 to 10 THz. Terahertz science and technology have quickly become research highlights over the past several years. A host of THz emitters based on different technologies are being developed [1]. Among them, the THz-FEL is a good candidate technology with favorable properties such as high peak brightness, a short pulse, and wavelength tunability. The development of THz-FEL, however, is constrained by the need for a huge facility and substantial funds. The most important task in THz-FEL development are to make the THz-FEL facility compact and to increase the output power.

The power emitted from an electron bunch can be expressed by,

$$W = W_1\left[N_e + N_e(N_e - 1)B(\omega)\right] \qquad (1)$$

where w_1 is the power from one electron, Ne is number of electrons, ω is the frequency of emitted radiation, $B(\omega)$ is the bunching factor

$$B(\omega) = \frac{1}{N_e}\sum_{j=1}^{N_e} e^{i\frac{\omega}{c}z_j} \qquad (2)$$

z_j is the longitudinal position of the j^{th} electron relative to the reference electron in a bunch. We can find that

If bunching $\langle z_j\rangle$ is much longer than $2\pi c/\omega$, $B(\omega) \sim 0$, $W \propto Ne$, which is spontaneous radiation;

If bunching $\langle z_j\rangle$ is much shorter than $2\pi c/\omega$, $B(\omega) \sim 1$, $W \propto Ne^2$, which is coherent radiation.

The bunching is therefore the most essential process within the FEL. Generally speaking, an electron bunch is longitudinally uniform (or Gaussian) before it passes into the wiggler. Once the electron beam is inside the wiggler, the wiggler magnetic field induces it to wiggle forward. The electron beam initially emits spontaneous radiation. The radiation field and wiggler field induce the electron bunch to gradually gather electrons into thousands of slices with spacing at the radiation wavelength. These slices radiate at the same phase as each other, forming what is termed super-radiation. Without the micro-bunching process, significant FEL radiation power cannot be obtained. Only a few FEL facilities are established in the world . Most of them are FEL oscillators operating at infrared spectrum. An FEL oscillator requires a large number of long macro-bunches, each consisting of thousands of micro-bunches. The micro-bunching process takes longer when carried out within a macro-bunch. The upstream micro-bunches in the macro-bunch contribute almost solely to the micro-bunching process and do very little to augment the radiation power. Yet the downstream micro-bunches in the macro-bunch can be micro-bunched into slices in the wiggler and thereby induced to super-radiate significant power. There are now several high-gain FEL facilities in operation at VUV, soft X-ray, and even hard X-ray spectra. They work in both the HGHG [2] and SASE [3] [4] [5] schemes. The HGHG FEL scheme relies on a complicated setup for micro-bunching the electron beam.

In the SASE FEL scheme, the micro-bunching process takes place along a long wiggler. The bunch can be micro-bunched into slices gradually at the head of the wiggler. The super-radiation grows stronger and stronger as the beam passes through the long wiggler, reaching saturation at the end. The FEL oscillator requires macro-bunches of sufficient length in the time domain, while the SASE FEL requires a wiggler of sufficient length in the space domain. The photocathode RF gun has evolved into a mature and reliable electron source. The time structure of the electron bunches from the photocathode depends on the laser pulse structure, and the accelerating process in the gun only slightly alters the electron bunch. In the following simulation we find that the time structure of the electron bunches can be adequately maintained at the exit of the RF gun and adjusted by changing the RF phase, bunch charge, and so on. If we use a driving laser with a ~THz pulse repetition rate we can generate electron micro-bunches at a ~THz repetition rate. By doing so, we can quickly achieve super-radiation up to the point of saturation within a short wiggler at the THz spectrum. The maximum pulse repetition rate of the available

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commercial laser is only several tens of GHz, or orders of magnitude lower than the THz range. Several optical technologies have been proposed for the production and handling of laser pulses at the THz repetition rate [6] [7]. In section II of this paper we describe an optical technology to handle a laser from a single pulse into a pulse sequence at a repetition rate at the THz level. The laser pulse sequence is used as the driving laser for the photocathode RF gun. Section III presents the detailed beam dynamics for the micro-bunch train in the RF gun. The pre-micro-bunched electron beam from the RF gun enters a wiggler and immediately super-radiates within it. Section IV presents the super-radiation process and saturation power from the pre-micro-bunched electron beam. Finally, section V presents our conclusions and discussions on this compact THz FEL scheme.

OPTICAL TECHNOLOGY TO GENERATE LASER PULSE SEQUENCE

As Figure 1 shows, a four-stage optical system can be used to split a laser pulse and generate a 16-pulse train. The system is composed of four polarizing beam splitters (PBS), four half-wave plates, and four optical delay lines. The full s-polarization is rotated to a 45-degree polarization with the first half-wave plate and then divided into an s-polarized pulse and a p-polarized pulse with the first PBS. The s-polarized pulse is delayed by Optical delay line 1 and then combined with the p-polarized pulse after the next PBS. After stage-1, a single laser pulse splits into two pulses. The time spacing (spacing-1) between the two pulses can be adjusted by delay line-1. In stage-2, a four-pulse train is generated with the same optical components. This train is composed of two groups, each of which has two pulses. The time spacing (spacing-2) between the two groups can be adjusted by optical delay line-2. After stage-3, an 8-pulse train can be generated and the time space (spacing-3) can be adjusted by optical delay line-3. In the same way, we can generate a 16-pulse laser train and adjust the time spacing (spacing-4) by optical delay line-4.

The following calculation focuses on FEL generation at 2 THz. The wavelength corresponding to 150 μm, the time spacing between the laser pulses is 500 fs, the laser pulse is Gaussian, and σt is 50 fs. The cathode response time in the electron emission from the cathode is very important for this scheme. If the response time isn't short enough, laser pulses with a time structure cannot generate an electron beam with the same time structure from the cathode. Because the response time of the Cu cathode is at the fs level illuminated by the 266 nm laser, we select Cu for the photocathode in the RF gun. The quantum efficiency (QE) of the Cu cathode is quite low, at about 0.02%. High-power THz radiation from the wiggler requires a high-current electron beam from the RF gun. A high-current electron beam, meanwhile, requires high-power laser pulses. A high-power laser from the above splitter system would potentially cause problems for the optical components, while a high-current electron beam from the RF gun would make it very difficult to accelerate and focus in the gun cavity and wiggler. In our calculation we assume a total charge of 200 pC per train. The required power of the laser pulse should be 5 μJ. Figure 2 shows the time structure of the 16-pulse sequence and a single pulse within the sequence. More pulses in the sequence would require more optical delay lines, and this would destabilize the system [8]. A laser sequence with more pulses would also require too much time for an S-band RF gun. Here we study a 16-pulse sequence, a sequence that corresponds to about 8 ps in time as our baseline.

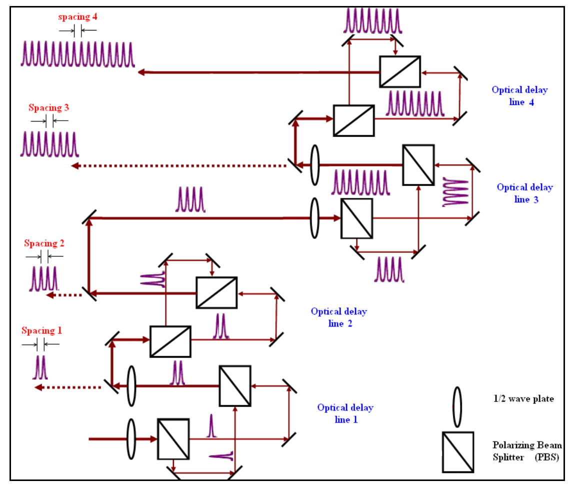

Figure 1: optical laser system for 16-pulse train.

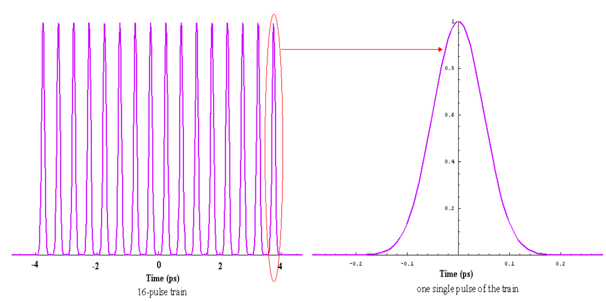

Figure 2: A 16-pulse laser sequence and a single pulse of the sequence.

BEAM DYNAMICS OF THE MICRO-BUNCH TRAIN IN THE RF GUN

An S-band 1.6-cell RF gun and solenoid are used as an electron source. The wiggler is positioned just downstream of the solenoid, with a distance of 50 cm between the wiggler entrance and cathode surface. Figure 3 shows the layout of the whole facility. The RF field of the gun and magnetic field of the solenoid are similar to those of the KEK/BNL gun [9]. The peak RF field gradient at the cathode surface is 100 MV/m, hence the energy of the electron beam from the gun is about 4.8 MeV. The solenoid focuses the electron beam into the waist at the wiggler entrance. In addition to compensating the beam emittance in this scheme, the solenoid also fundamentally serves as a focusing lens. Figure 4 shows a

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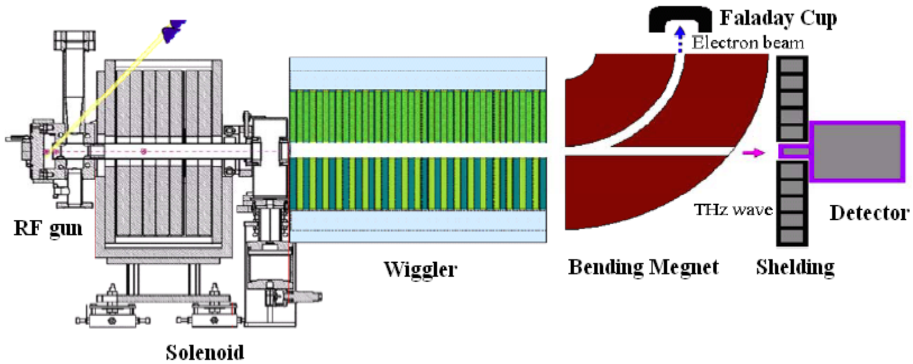

Figure 3: Layout of the proposed THz-FEL facility.

16-micro-bunch train on the cathode surface and its bunching factor. The bunching factor at 2 THz is more than 0.8, and there are several high harmonic components with high bunching factors, as well. After the acceleration and focusing in the gun, we note a considerable deterioration in the micro-bunch structure (see Figure 5). Even so, the bunching factor at 2 THz is still higher than 0.446. All of the higher harmonic components except the second one disappear.

We focus specifically on the longitudinal phase space of the beam in the RF gun, the RF effect and space charge effect are the most dominant effects on the beam during the accelerating process. The space charge effect is certainly to induce repulsion between the micro-bunches, and the RF effect on the beam depends on the injection phase. For a micro-bunch train with a charge of 200 pC, If the train is injected into the gun at RF phase of 20 degree, the total effect keeps the peak of bunching factor at the same frequency of 2 THz; If the train is injected into the gun at a RF phase less than 20 degree, the peak of bunching factor moves to a frequency higher than 2 THz; If the injection phase is set to a value more than 20 degree,
the peak bunching factor moves to a lower frequency.
As the charge of the bunch train changes, the optimized injection phase changes correspondently [10].

SUPER-RADIATION FROM THE ELECTRON BEAM IN THE WIGGLER

The 16-micro-bunch train stays well micro-bunched at the wiggler entrance, with a bunching factor of 0.446. GENESIS code is used to simulate the radiation process in the wiggler. GENESIS directly calls on the output file from PARMELA describing the pre-micro-bunched train. Because these micro-bunches radiate in the same phase, the radiation power increases quickly, as shown in Figure 6. The saturation at the 150 μm wavelength is achieved within a 0.4 meter length of the wiggler. The saturation power is 0.68 MW and the corresponding energy is 5.24 μJ/pulse. The wiggler parameters in this simulation are a period length of 15 mm, K value of 0.99, and a planar type.

Figure 7 shows radiation power from an electron bunch without a micro-bunch structure at the wiggler entrance. train. And like the 16-bunch train, it is also focused into

The single bunch has the same charge, the same bunch length, and the same beam energy as the 16-micro-bunch

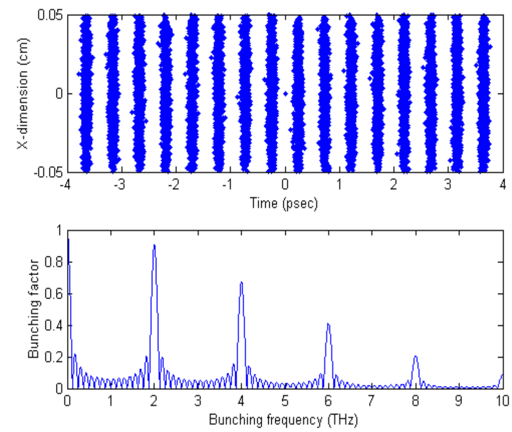

Figure 4: Micro-bunch train and bunching factor at the cathode surface.

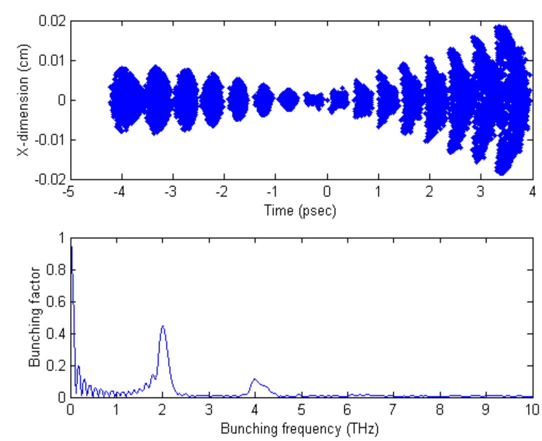

Figure 5: Micro bunches and bunching factor at the wiggler entrance (injection phase is set to 20 degree).

the waist at the wiggler entrance. The bunching factor at 2 THz is almost zero, and the micro-bunching inside the bunch takes place gradually within the first 1 meter of the wiggler. The radiation power is initially very low and begins to increase slowly as the micro-bunching increases. At the 3 meter position it reaches 0.19 MW.

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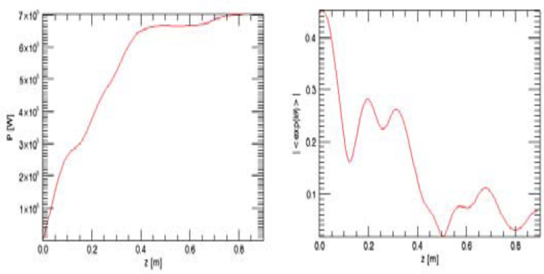

Figure 6: THz FEL power and bunching factor along the wiggler for the 16-micro-bunch train.

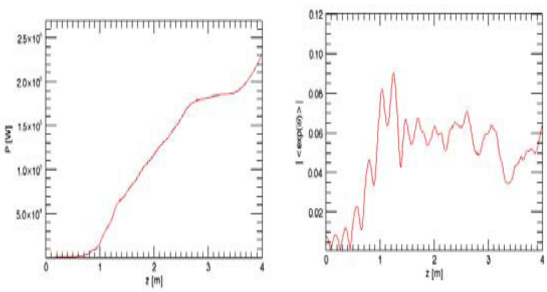

Figure 7: THz FEL power and bunching factor along the wiggler for the single bunch.

DISCUSSION & CONCLUSION

One advantage of the FEL is a tunable wavelength. The FEL wavelength generally depends on the beam energy and the wiggler parameter, as expressed in formula (3):

$$\lambda_s = \frac{\lambda_w}{2\gamma^2}(1+K^2) \quad (3)$$

where λ_w is the wiggler period, γ is the relative beam energy, and K is the wiggler parameter.

For the pre-micro-bunched THz FEL, the beam is pre-micro-bunched at a certain repetition rate before it enters the wiggler. For this reason, the wavelength corresponding to this repetition rate must match the wavelength dominated by the beam energy γ, wiggler λ_w, and K in formula (3). Super-radiation and saturation within a short wiggler will only be achievable if these wavelengths match each other well. We can use several possible methods to accomplish this matching.

(1) First and fundamentally, we can change the delay line of the laser system to adjust the repetition rate of the laser pulse. All the delay lines should be tuned precisely at the same time.

(2) We can insert one α-magnet between the RF gun and wiggler to adjust the repetition rate of the pre-micro-bunched electron beam.

(3) As the above simulation results show, we can change the injection RF phase to tune the repetition rate. In doing so, however, we must take steps to minimize the change of the beam energy.

(4) The easiest method is to change the K value in the operation by adjusting the wiggler gap.

In conclusion, a simple and relative mature laser splitter technology can be used to generate a laser pulse sequence with a pulse repetition rate at ~THz frequency. The laser pulse sequence illuminates the photocathode of the RF gun to generate the micro-bunched electron beam. The electron beam stays favorably micro-bunched in the accelerating process within the gun, hence the bunching factor is significantly high at the wiggler entrance. The micro-bunch electron beam achieves super-radiation immediately upon entering the wiggler. In a simulation of a 16-micro-bunch train with a 200 pC charge, the bunching factor at the entrance of the wiggler was 0.446 at 2 THz. THz radiations at a 150 μm wavelength with a radiation power of 0.68 MW can be produced along a 0.4-meter length of the wiggler. Taking account of the RF gun and solenoid, the whole THz FEL facility is less than 1 meter long, or small enough to scale to a tabletop.

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