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THE RADIATION SOURCE FOR A PRE-BUNCHED THz FREE ELECTRON LASER*

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Abstract

Electron beams, generated in a photoinjector and bunched at terahertz (THz) frequency, will excite the coherent THz radiation when entering an undulator. We present a scheme of the radiation source for the pre-bunched THz free electron laser (FEL). The physical design of electron source is described in detail. The radiation frequency is widely tunable by both the pulse train tuning and the undulator gap tuning. It is simulation proved that the radiation power is greatly enhanced in our scheme.

INTRODUCTION

Terahertz (THz) radiation has attracted more and more attention because it holds the promise of enabling various new scientific and industrial applications [1–3]. A new high throughput material characterization system is under development at National Synchrotron Radiation Laboratory (NSRL), University of Science and Technology of China. It is a multiple light source which will supply a time resolved pump laser, a broad-band THz source and a pre-bunched THz free electron laser (FEL). The pre-bunched THz FEL is an intense narrowband THz source with a broad tuning range of radiation frequency. It is a single-pass FEL driven by a THz-pulse train photoinjector, in which the electron beam is pre-bunched before entering the undulator and will excite coherent emission during the whole radiation process.

Figure 1 gives the overview of the THz FEL, which is composed of a photocathode rf gun illuminated by a THz-pulse-train laser, solenoids for focusing the electron beam, a short linac to compensate the energy spread and a short undulator to exite the radiation. It is a very compact THz source as the total length is about 3.5 meters.

Using this laser pulse train to illuminate the cathode, THz electron microbunch train emits, then is accelerated in the rf gun and the linear accelrator (linac), which is capable of satisfying the requirement of the electron energy for THz FEL. Downstream the linac, the electron pulse train passes through a short undulator to generate the coherent THz radiation. To realize the intense THz radiation with a broad tunable frequencies range, the key is tuning the optical delay lines of the laser and tuning the undulator gap.

For a certain frequency f, the total coherent radiation power P of the undulator can be expressed by [4]

$$P = NP_0[1 + (N - 1)b^2(f)] \tag{1}$$

where N is the electron numbers in the bunch, P_0 is the incoherent radiation power of a single electron, which is proportional to N^2, and b is the bunching factor describing the longitudinal electron density distribution in the bunch. Assumed the pre-bunched beam consists of n Gaussian microbunches with rms pulse length of σ_t, spacing by Δt temporal interval, the bunching factor can be written as [4]

$$b(f) = \frac{1}{n}\left|\frac{\sin \pi n f \Delta t}{\sin \pi f \Delta t}\right| e^{(-(2\pi f \sigma_t)^2/2)} \tag{2}$$

The pre-bunched beam bunches at the fundamental frequency ($f = 1/\Delta t$) and high harmonics ($f = m/\Delta t$, $m = 2, 3 \ldots$). Thus, a pre-bunched electron beam with THz-pulse-train structure will significantly enhance the total radiation power.

PHYSICAL DESIGN OF ELECTRON SOURCE

To obtain intense FEL radiation, one should increase the bunching factor and electron bunch charge, which are restrained by the space charge effect. The photoinjector is ultilized to generate a highly bunched electron beam by accelerating the electron rapidly and minimizing the space charge effect. Two solenoids surrounding the gun and linac respectively are used to control the electron bunch size through the undulator. The design requirements of the electron source are shown in Table 1.

Table 1: Design Requirements

Parameter	Value
electron energy	11 to 18 MeV
microbunches	16
total charge	240 pC
fundamental frequency	0.5 to 3.0 THz
bunching factor	≥ 0.4

The photocathode rf gun is a 1.6-cell, 2856 MHz structure with peak accelerating gradient of 110 MV/m at the cathode (copper). The linac is a 90 cm, 2856 MHz travelling wave structure with a variable gradient of 10 to 20 MV/m. The linac is located 50 cm downstream the cathode, considering a rapid acceleration, and which is limited by the facility space.

The electron distribution is determined by the laser pulse. The laser micropulse is a Gaussian pulse in longitudinal with the rms width of 30 fs, and a truncated Gaussian in transverse with radius of 2 mm. The laser pulse train is

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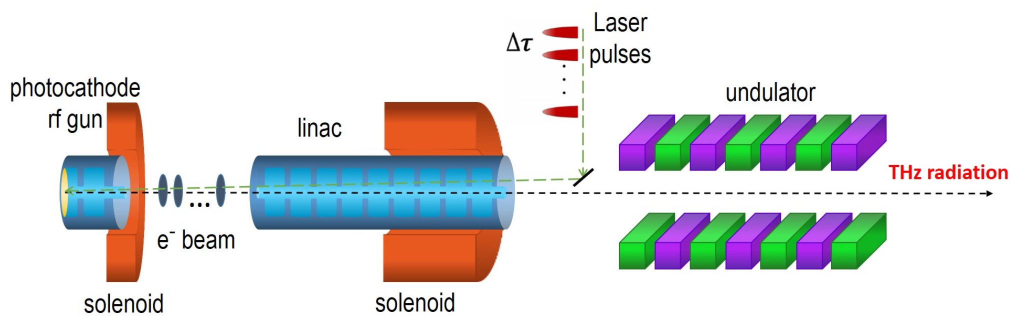

Figure 1: Overview of the pre-bunched THz FEL.

Table 2: Beam Line Setting for the 2 THz Case

Parameter	Value
linac gradient	20 MV/m
linac phase	-10 degree off crest
gun phase	17 degree off crest
strength of gun solenoid	1750 Gauss
strength of linac solenoid	700 Gauss

consist of 16 micropulses. We have chosen a fs laser with a wavelength of 266 nm, and an energy on the cathode of 112 μJ. For the typical fundamental frequencies of 0.5 THz, 1.0 THz, 2.5 THz and 3.0 THz, the time intervals of laser pulse trains are 2.0 ps, 1.0 ps, 0.4 ps and 0.33 ps respectively. Radiation between 3.0 and 5.0 THz is realized by the second harmonic of a fundamental mode.

Design Results for 2 THz Case

In this subsection, we take the bunch train spaced by 0.5-ps intervals with the beam energy of 18 MeV as a typical example. The simulation is completed by ASTRA [5] code. The parameters of each component are listed in Table 2.

The time distribution of bunch train at the cathode and the undulator entrance (injector exit) are compared in Fig. 2. One can find that each microbunch has a very narrow width and a quasiequal spacing time, which contributes to the high bunching factors in the first several harmonics as given in Fig. 3. The bunching factor is 0.61 at fundamental mode of 2.04 THz and 0.15 at second harmonic of 4.05 THz, respectively. In addition, the bunching frequency is shifted to a slightly higher one due to the velocity bunching.

In the rf gun, the electron energies of the microbunches are chirped leading to a large energy spread which is disadvantaged for the FEL radiation. The beam energy spread could be compensated by a linac when injected at a proper phase (see Fig. 4).

Beam size through the undulator is minimized to optimize the radiation power and FEL transverse character. The beam size evolution is shown in Fig. 5.

For other bunching frequencies, the beam line has been designed in a similar way. It is notable that for frequency below 1.0 THz, a lower electron energy is required so that

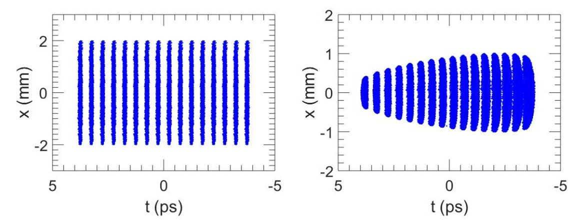

Figure 2: Time distribution of bunch train at the cathode (left) and the undulator (right).

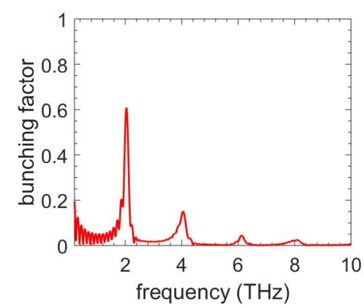

Figure 3: Bunching factor @ 2 THz.

the accelerating gradient is set as 10 MV/m, otherwise the gradient is 20 MV/m.

COHERENT RADIATION

A planar undulator with 54-mm period and 1.0-m length is optimally used for covering a broad radiation frequency range. Here, we give the coherent radiation design of the 2-THz scenario, which is simulated by the code GENESIS [6]. When the overall radiation characteristics are optimized, a 1.35-MW peak power (pulse energy of 13.72 μJ) with a 4.5% bandwidth could be realized. (When the radiation power is set as the optimization object, a maximum peak power of 4 MW would be reached.) The time structure and spectrum in the fundamental mode of the output pulses at the undulator exit are presented in Fig. 6. The radiation distribution at undulator exit is shown in Fig. 7. For the second harmonic wave, the radiation peak power is also considerable.

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Table 3: Paramater Errors

Performance	Error source	Error	Comment
Radiation frequency		0.6%	less than the radiation bandwidth
Radiation power	charge,bunching factor	3.9%	rms value is 4.0%
	electron beam misalignment	1.0%	
Light spot misalignment	spot center	10 μm	
	light emission angle	10 μrad	

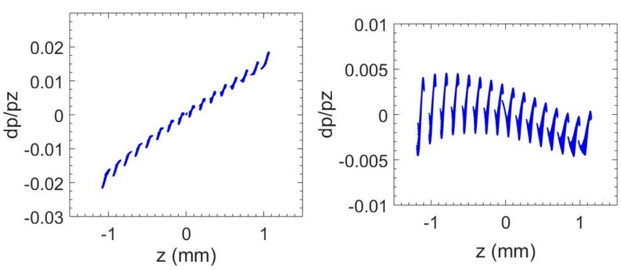

Figure 4: Energy spread at gun exit (left) and at undulator entrance (right).

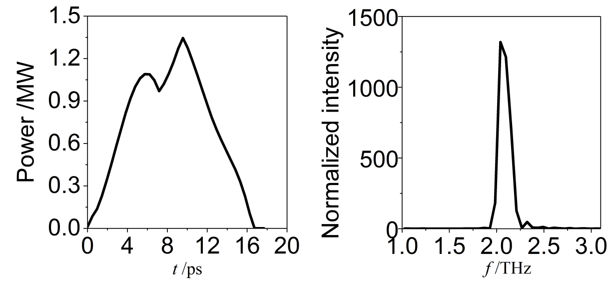

Figure 6: Time structure (left) and the output FEL pulse (right) for 2.0 THz.

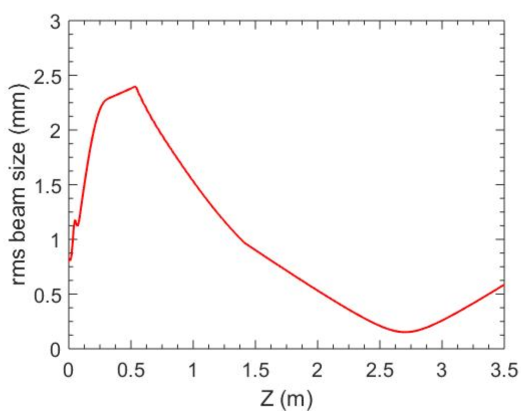

Figure 5: RMS beam size evolution.

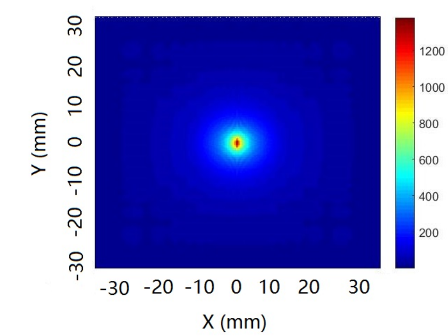

Figure 7: Radiation distribution for 2.0 THz.

ERROR ANALYSIS

The FEL performance jitter primarily originates from two aspects, which are the errors of the electron beam and the errors of the undulator. Based on the deviation tolerance of the electron beam and the undulator, the errors of parameters are listed in Table 3.

CONCLUSION

We introduced the physical design of the radiation source for a pre-bunched THz FEL. A compact THz source with the peak power of a few MW, the pulse energy of several tens of μJ, the bandwidth of a few percent, and tunable frequency range of 0.5-5 THz could be achieved. All the design results have satisfied the requirement of the project. Technical design is in progress, and debugging and laser output is expected in 2020.

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