DESIGN OF FEL BY THE EEHG SCHEME AT TSINGHUA UNIVERSITY*

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Abstract

We adopt the Echo-Enabled Harmonic Generation (EEHG) scheme proposed by D. Xiang to design a device to generate intense narrow-band THz radiation based on the Tsinghua Thomson scattering X-ray (TTX) electron beam [1]. In this scheme the 50 MeV electron beam is firstly energy-modulated by two lasers with wavelengths of 800nm and 1560nm respectively. Then the modulated electron beam is sent into a chicane whose R_{56} is 20 mm to convent the energy modulation to density modulation. At last the density-modulated electron beam is sent to a radiator which is tuned to 31.2 μm and generates the narrow-band THz radiation with the peak power of 8 MW. We simulate above laser-beam interaction using GENESIS 1.3.

INTRODUCTION

There is a growing interest in generating high power and narrow-band THz radiation which has wide applications in nondestructive imaging and spectroscopic studies of materials and molecules. The typically category aims to provide such powerful narrow-band THz radiation using bunched electron beam with a density modulation repeated at THz frequency. Conventional methods are to use a train of laser pulses to generate a train of electron beams repeated at THz frequency or use a shaped laser with a quasisinusoidal envelope at THz frequency to modulate the relativistic electron beam [2].

D. Xiang proposed a scheme to generate intense narrow-band THz radiation [2]. The scheme is similar to Echo-Enabled Harmonic Generation (EEHG) except that there is only one dispersion section and the aim is to down-convert the frequencies of the lasers. In this scheme the electron beam is firstly energy-modulated by two lasers with the wave number of k_1 and k_2, respectively. The beam acquires energy modulation at wave number $k = n\ k_1+m\ k_2$, where n and m are positive or negative integers. After passing through a dispersion section the energy modulation is converted to density modulation. By properly choosing the parameters of the lasers and dispersion section, the electron beam can be density-modulated at THz frequency and generates powerful narrow-band THz radiation. We can easily tune the central frequency of THz radiation by varying the wavelength of lasers and the strength of dispersion section to cover the whole THz range.

We generate high quality 50MeV electron beam with the slice energy spread of 0.01% using the photo cathode and traveling-wave linac in ACC lab at Tsinghua University [1]. Employing the high quality electron beam we choose reasonable parameters to generate THz radiation using D. Xiang's scheme. We use the upgraded code GENESIS 1.3 to simulate the whole process. We encounter some puzzles when simulating because GENESIS 1.3 only allows the up-conversion to a higher harmonics. We have written a code to read the output of particle distributions generated by GENESIS 1.3 and rewrite it for a next run.

EEHG SCHEME

The scheme proposed by D. Xiang for generating THz radiation is shown in Fig.1. It consists of two modulators and one dispersion section. Following the assumptions and derivations in Ref. [2], we can write the particle distribution function at the end of the dispersion section as

$$f_f(z,p) = \frac{N_0}{\sqrt{2\pi}}\exp[-\frac{1}{2}[p - A_1\sin(k_1 z - Bp) - A_2\sin(k_2 z - KBp + \phi)]^2] \quad (1)$$

where A_1 and A_2 are the dimensionless modulation amplitude in modulator 1 and modulator 2 respectively, $B = R_{56}k_2\,\sigma_E/E_0$, $K = k_1/k_2$ [2]. The bunching factor for each harmonic can be written as

$$b_{n,m} = |J_n\left[(n+Km)A_1B\right]\times J_m\left[(n+Km)A_2B\right] e^{-(1/2)\left[(n+Km)B\right]^2}| \quad (2)$$

We obtain the following rules to maximize the bunching factor $b_{n,m}$,

$$\begin{cases}(n+Km)A_1B = x_n \\ (n+Km)A_2B = x_m\end{cases} \quad (3)$$

Obviously, the value of A_2 needs to be as large as possible to maximize $e^{-(1/2)\left[(n+Km)B\right]^2}$. However, if A_2 is too large the energy spread introduced in the modulator 2 will degenerate the exponential process in the radiator.

By choosing the optimized parameters of A_1, A_2 and B, the maximum bunching factor can reach the order of 0.1 with the fixed values of n, m and K.

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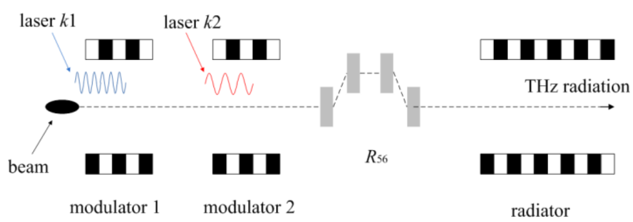

Figure 1: Scheme proposed by D. Xiang for generating THz radiation

PARAMETERS

The main parameters of the electron beam generated in ACC lab are listed in Table 1. Based on above rules we choose the optimized parameters of A_1=3, A_2=5.74, B=19.95. The parameters of the lasers, modulators and chicane are listed in Table 1.

Table 1: Main Parameters of the Laser-Modulated THz Source

Parameters	Values
Electron beam energy	50 MeV
Slice energy spread	0.01%
Peak current	600 A
Bunch length (rms)	1 fs
Normalized transverse emittance	2 mm mrad
Transverse spot size (rms)	30 μm
Laser1 wavelength	800 nm
Laser1 power	1.29 MW
Laser1 Rayleigh length	0.5 m
Modulator1 N_p	5
Modulator1 λ_u	1.2 cm
Modulator1 a_w	0.526
Laser2 wavelength	1560 nm
Laser2 power	2 MW
Laser2 Rayleigh length	0.5 m
Modulator 2 N_p	5
Modulator 2 λ_u	2.0 cm
Modulator 2 a_w	0.7
R_{56} for dispersion section	25.4 mm
Radiator λ_u	3.0 cm
Radiator a_w	4.35

SIMULATION AND RESULTS

The simulation is consisted of three separate runs. In the first run, the energy modulation from the 800 nm seed laser in the first modulator is simulated and the particle distribution is dumped at the exit of the first modulator. The particle distribution is imported and sent to the second modulator for further energy modulation. At the exit of the second modulator, the particle is dumped again. Finally, the particle distribution is reimported for the third run. But GENESIS 1.3 can only do harmonic simulation, i.e. the laser frequency in next run must be the integer multiples of the frequency in previous run. In our scheme the laser wavelength in the first modulator, the second modulator and radiator are 0.8μm, 1.56μm and 31.2μm, respectively. We cannot simulate this process using GENESIS 1.3 directly. In order to simulate this down–convert frequency process using GENESIS 1.3, we read the particle distribution file and rewrite it. Take as an example how to rewrite the particle distribution file generated in the first run for the second run, the method is described as follows:

- Read the binary particle distribution file .dpa generated by the first run.
- Decide which slice a particle belongs to in the new wavelength. Let θ_j denotes the particle phase in the first modulator. First, add $(2N-1)\pi$ to θ_j, where N is the number of slice which the particle is belonged to in the first modulator. Second, multiple θ_j by K. At last, $\exists M$, $s.t.$ $\left[\theta_j - 2(M-1)\pi\right] \in [0, 2\pi]$, then M is the new number of slice which the particle belongs to in the second modulator. And subtract $(2M-1)\pi$ from θ_j.
- The above transformation may induce a little difference in the number of particles in each slice. However GENESIS 1.3 needs every slice has the same number of particles. We need to find the minimum number of particles in all slices and eliminate some particles randomly to keep the number of particles the same in each slice.
- Import the new binary particle distribution file to the next run.

Using above method, we simulate the whole scheme successfully.

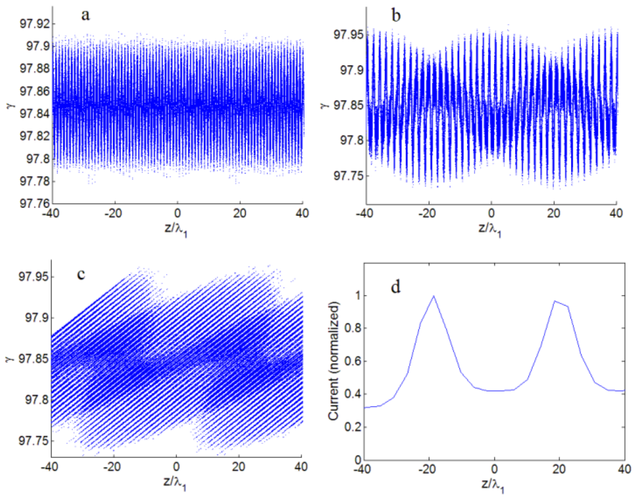

Figure 2: The phase space of the beam: (a) phase space at the exit of modulator1; (b) phase space at the exit of modulator2; (c) phase space at the exit of the dispersion section; (d) current distribution at the exit of the dispersion section.

The particle distributions at different positions are shown in Fig. 2. We can see the electron beam acquire density modulation repeated at 9.6 THz after passing through the chicane. The simulation results of THz radiation in radiator are shown in Fig. 3. In Fig. 3 (d) we can see the simulation value of bunching factor for 9.6 THz after passing through the chicane is 0.22. It is close to the value of 0.239 given by (2). The modulated beam generates intense narrow-band THz radiation in 15~20 undulator periods in the radiator. The peak power of THz radiation is 8 MW and the bandwidth of THz radiation is 2%.

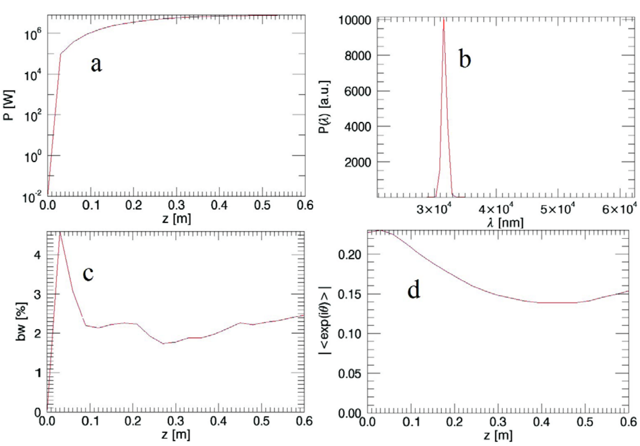

Figure 3: (a) The power in the radiator; (b) the spectrum at z=0.3m; (c) the bandwidth in the radiator; (d) the bunching factor in the radiator.

The transverse size of the electron beam in x and y directions are shown in Fig. 4. We can see that because the radiator is short there is no need to use the FODO lattice to control the rms size of the beam in x direction. The rms size of the beam in y direction is oscillating because of the self-focusing of the undulator.

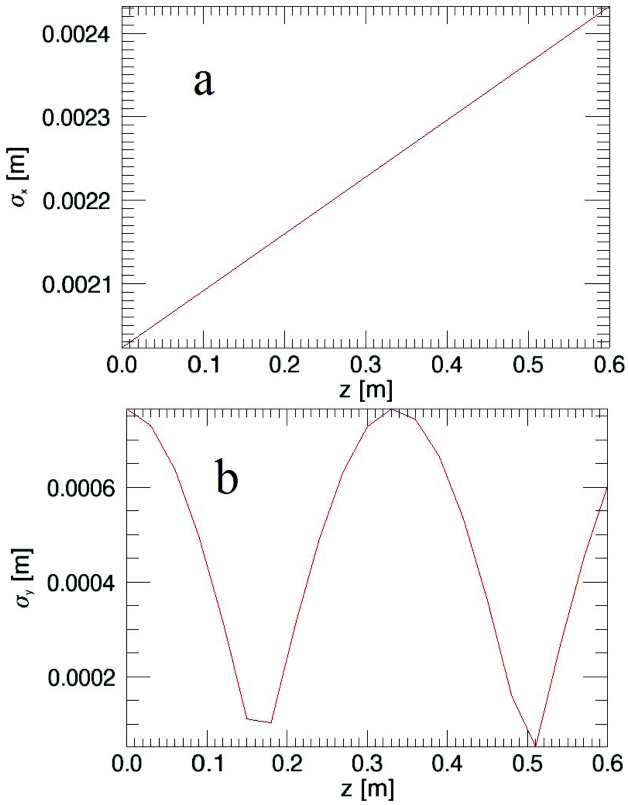

Figure 4: (a) The rms size of the beam in x direction in the radiator; (b) the rms size of the beam in y direction in the radiator.

CONCLUSIONS

Based on the electron beam generated at Tsinghua University, we have designed a FEL system by the EEHG scheme to generate intense narrow-band THz radiation. We simulate the whole scheme using GENESIS 1.3 with some minor manipulations.

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