SLIPPAGE EFFECT ON THE TABLE-TOP THz FEL AMPLIFIER PROJECT IN KYOTO UNIVERSITY

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Abstract

We proposed a table-top seeded THz FEL amplifier using a multi-bunch photocathode RF gun and injection-seeded terahertz parametric generator. In order to evaluate possibility of the tabletop THz FEL amplifier, start-to-end simulation of FEL taking a slippage effect into account have been performed.

It was numerically found that even in a large-slippage regime, the peak output power of about 350 kW at 185 μm was expected by improving beam focusing.

INTRODUCTION

Since many rotation and vibration modes of the molecule exist in the THz region, a compact, monochromatic, wavelength tunable, and high-power THz source will be a one of key technologies in THz science. A FEL THz source is the most powerful source in this region, and several works have been carried out to realize compact THz FEL[1 -4], and we also proposed a compact seeded THz FEL amplifier[5] using a photocathode RF gun and a compact staggered undulator using high TC bulk superconductor[6, 7] and injection-seeded terahertz parametric generator (is-TPG)[8].

In case of long wavelength FEL, slippage effect; electron bunch slips back over the optical field by one wavelength in each wiggle motion, causes a serious reduction in the FEL gain. Since total slippage length of the optical pulse S is written as $S = N \cdot \lambda_R$, where λ_R is the wavelength of radiation, N is the number of undulator period, the slippage length sometimes exceeds electron bunch length for long wavelength FEL, and thus the FEL interaction does not persists along the whole undulator.

In this work, we performed start-to-end simulation on the THz FEL amplifier planned at Kyoto University. In order to estimate the performance, THz power evolution in a large-slippage regime were calculated. Expected performance and strategy to increase THz power will be discussed in this paper.

TABLE-TOP FEL AMPLIFIRE

The THz FEL amplifier consists of a photocathode RF gun, an is-TPG seed THz light generator, a focusing solenoid magnet, and a Halbach undulator. A schematic drawing of the THz amplifier is shown in fig. 1. The seed THz light will be used to overcome the disadvantage of broad spectrum of a self-amplified spontaneous emission and reduce required length of the undulator. In the present proposal, the RF gun and the undulator will be aligned on a single axis, and the seed THz light is injected using catoptric system with a hollow mirror on the beam axis.

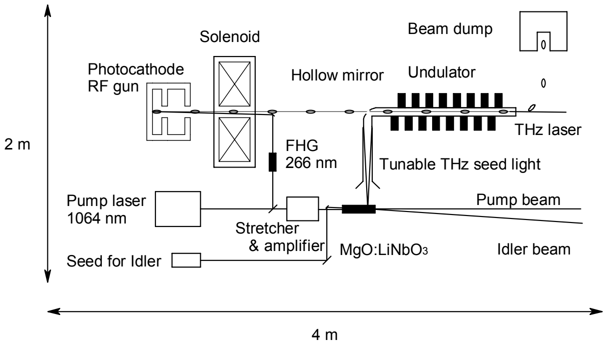

Figure 1: Schematic design of the Table Top THz FEL amplifier. It consists of a BNL type 1.6 cell photocathode RF gun with focusing solenoid, is-TPG THz seed generator, drive lasers both for the RF gun and the is-TPG, and a Halbach undulator. All the accelerator components can be put on an optical table of 2 m × 4m.

In our proposal, the improved BNL type 1.6-cell photocathode RF gun[9] which was developed under the collaboration of KEK-ATF, AIST, Waseda Univ., and Osaka Univ. A $CsTe_2$ photocathode and a UV excitation laser will be used. In case of the long wavelength FEL, if the electron bunch is strongly compressed in longitudinal, electron beam can not interact with optical field efficiently due to the strong slippage effect. Hence the bunch length of 3.47 ps (1.04 mm) which is about 5 times longer than the THz wavelength is assumed as the design value. The solenoid magnet attached to the RF gun will be used to focus the electron beam and control beam envelope in the undulator. A 2.5 m long in vacuum type Halbach undulator with 125 periods and undulator parameter K of 2.0 is assumed for the numerical estimation of the performance of the FEL amplifier. The undulator gap was obtained as 4.8 mm from Halbach formula[10]. It is noted that the number of the undulator

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period was obtained by the simple estimation without slippage effect[5]. The is-TPG is a tunable THz light generator based on on stimulated polariton scattering in a MgO:LiNbO$_3$ crystal. Tunability can be realized by changing the wavelength of seed laser for idler. The THz output power of 1.3 nJ per pulse was achieved with 34.5 mJ per pulse of pump laser and 50 mW of seed laser. The wide tunability from 125 to 430 μm has been reported[8]. Perfect synchronization between electron beam and the THz seed light can be automatically obtained by splitting seed laser from single the oscillator for the is-TPG and the pump laser for the photocathode. Since large spillage will arise in the undulator, laser pulse stretcher will be installed before the MgO:LiNbO$_3$ crystal.

NUMERICAL CALCULATION

Beam tracking simulation from the photocathode RF gun to the undulator entrance have been carried out using the simulation code PARMELA[11]. RF cavity voltage and laser injection phase ware fixed to 70 MV/m and 40 degree respectively[5]. Beam focusing effect for the FEL amplifier was studied by changing the solenoid magnetic field from 0.21 T to 0.23 T. Distance between the cathode surface to the undulator entrance was fixed to be 0.8 m. FEL gain and power evolutions were calculated by the 3D simulation code GENESIS 1.3[12] in time-dependent mode. In the calculation, radiation field and electron beam were sliced in each 0.62 ps. The field equations for a steady state are solved and then the field are copied to the next slice which electron beam slips to. The electron beam parameters calculated by PARMELA were taken over to the following FEL simulation. The power of the seed THz light was fixed to 0.2 W. Parameters used for beam tracking and FEL simulation are listed in tables 1 and 2. Parameters for the FEL simulations listed in table 2 were obtained under the assumption at the bunch charge of 1.0 nC and the solenoid field of 0.21 T respectively.

Table 1: Parameters for beam tracking

RF gun	Cavity voltage	70 MV/m
	Laser inj. phase	40 degree
	Laser spot size	2 mm ϕ
	Bunch charge	0.8, 1.0, 1.2 nC
	Solenoid field	0.21, 0.22, 0.23 T
Seed THz	Seed power	200 mW
	Frequency Wavelength	1.62 THz 185 μm
Undulator	Type	Halbach
	Period length	20 mm
	K value	2.0
	Number of period	125
	Gap	4.8 mm

Table 2: Parameters for FEL simulation

RF gun	Bunch charge	1 nC
	Solenoid field	0.21 T
Electron beam	Energy	6.25 MeV
	Energy spread	0.8% (rms)
	Norm. emittance (x)	1.77 π mm-mrad
	Norm. emittance (y)	1.63 π mm-mrad
	Beam size (x)	0.74 mm (rms)
	Beam size(y)	0.72 mm (rms)
	Twiss parameter (x)	2.95
	Twiss parameter (y)	1.95
	Peak current	288 A

RESULTS AND DISCUSSION

First, the power evolution of the THz laser has been calculated for the bunch charge of 1.0 nC and the solenoid field of 0.21 T. Longitudinal profiles of optical beam and electron beam at the exit of the undulator is shown in fig. 2. Owing to the large slippage in the undulator, the optical pulse length reached to 23 mm (full width) in advance of the electron bunch whose width of 1.04 mm (rms). The FEL peak power was calculated to be 5.1 kW, whereas the calculated power without slippage effect was several MW[5]. As the THz seed power of seed light was 0.20 W, the THz optical pulse was amplified about 4 orders of magnitude, but seems not to be saturated. Integrated radiation power was estimated to be 0.10 μJ. Because the electron bunch slips back over the optical field by 185 μm in each wiggle motion, each optical slice can efficiently interact with electron bunch only about 5 times in the undulator and travels in the undulator unattended with electron slice. In other words, history of the FEL interaction is recorded in the preceding optical slices. As travelling in the undulator, electron beam is micro-bunched and then the THz output power increases slowly. However, even with the micro-bunching effect, the THz output level is much smaller than the saturation level, because horizontal beam size increases again at latter part in the undulator and electron beam is lost in the beam duct, thus the peak current decreases as travelling in the undulator. Therefore, extending the period number of undulator will not be beneficial in a large slippage regime.

As the second step, in order achieve FEL saturation in the tabletop THz FEL amplifier, several numerical studies have been carried out without changing the layout of the components. The parameter scan has been performed by changing the bunch charge around 1 nC. Beam tracking simulation have been performed for different bunch charge; 0.8, 1.0, 1.2 nC as shown in fig. 3. Due to the deference in space charge effect, noticeable changes are obtained. When the bunch charge was changed from 1.0 to 1.2 nC, beam waist size was increased by 27 %. As the result, electron density decreased by about 26 % due to the space charge effect. On the contrary, charge reduction from 1.0 to 0.8 nC increased electron density by about 45 %. As described above, although the increment of the bunch charge increases the number of electrons, but not always increases the peak current density in the undulator. In order to evaluate the figure of merit on the FEL output power, FEL simulations have been carried out. Longitudinal profiles of the optical pulse and the electron beam for different bunch charges are shown in fig. 4. Since the bunch length is not affected by the bunch charge, the electron peak current linearly scales to the bunch charge. Despite the beam current increases by increasing the bunch charge from 1.0 to 1.2 nC, the FEL output decreases by 1 order of magnitude. On the other hand, when the bunch charge was reduced from 1.0 to 0.8 nC, the FEL output power was not strongly affected. Through the numerical simulations, it was numerically found that the effective electron beam density is quite important also in the large-slippage regime and the increment of the bunch charge will cause the negative effect. We can conclude that the electron beam density should be increased and that the long undulator is not effective in the large-slippage regime.

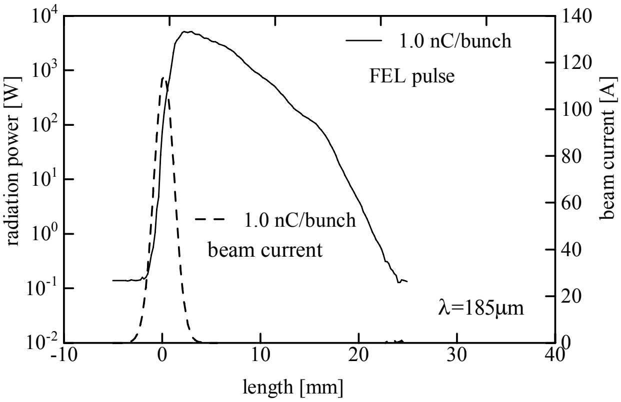

Figure 2: Longitudinal profiles of optical beam and electron beam at the exit of the undulator.

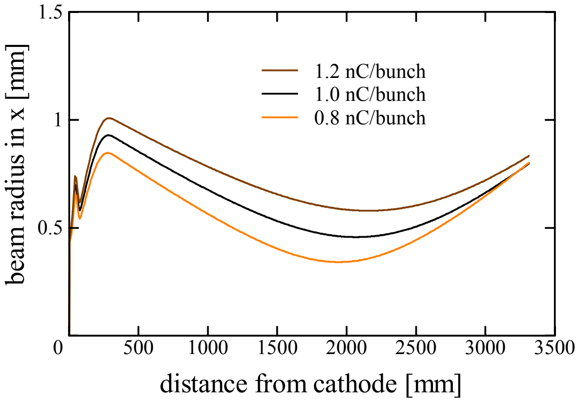

Figure 3: Evolutions of the beam size along the beam axis. The undulator is placed between 800 and 3300 mm.

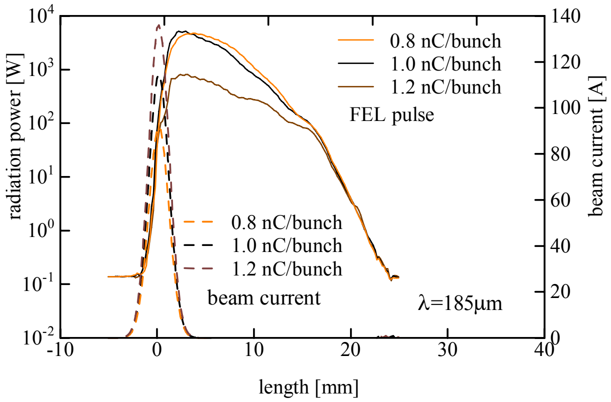

Figure 4: Longitudinal profiles of optical beam and electron beam at the exit of the undulator for different bunch charge.

As the third step, we redesigned the beam transport and the length of the undulator. Here the strategy was reducing the beam size by increasing the solenoid field and amplify the seed THz light with the compact undulator. We have performed the beam tracking simulation under the solenoid field of 0.23T as shown in fig. 5. The beam waist size was reduced by 64%, and thus the electron beam density at the beam waist was considerably increased by 7.6 times. Concerning the undulator length, the number of period was set to 80 in order to reduce the beam loss in the undulator. The FEL simulation has been carried out for 1.0 nC of the bunch charge and 0.23 T of the solenoid field. Longitudinal profile of the optical beam at the exit of the undulator is shown in fig. 6. As shown in fig. 6, the FEL peak power was considerably increased to 350 kW. It corresponds that the THz seed power was amplified about 6 orders of magnitude. However, the remarkable indication of FEL saturation such as the power oscillation post saturation was not confirmed.

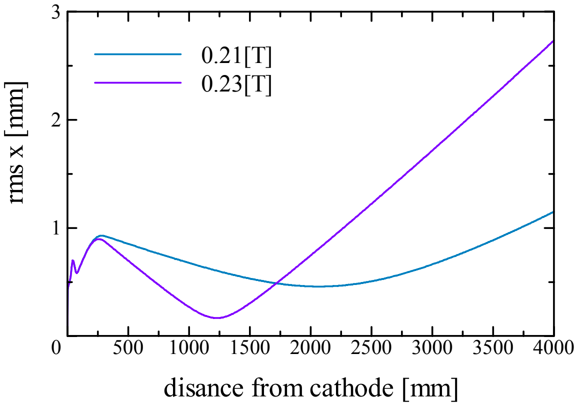

Figure 5: Evolutions of the beam size along the beam axis. The undulator is placed between 800 and 2400 mm.

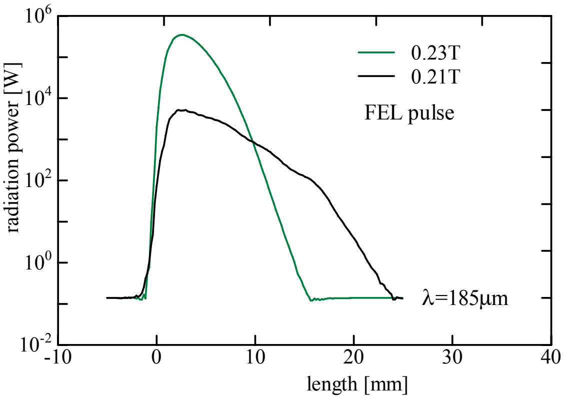

Figure 6: Longitudinal profiles of optical beam and electron beam at the exit of the undulator

CONCLUSION

We performed the start-to-end simulation on the THz FEL amplifier planned at Kyoto University. In this calculation, the slippage effect; which is serious especially in the long wavelength FEL was taken into account by using time-dependent mode of the 3D FEL simulation code GENESIS. Longitudinal profiles of the THz optical pulse has been calculated, and the characteristics of the FEL amplifier have been also studied. The output power of 5.1 kW was expected, but does not reach to power saturation. Through the investigation of the charge dependence, we could conclude that the electron beam density should be increased and that the long undulator is not effective in the large-slippage regime.

In order to increase the output power, we redesigned the beam transport and the undulator length. By increasing the solenoid field from 0.21 T to 0.23 T, the FEL output was increased from 5.1 kW to 350 kW. However, the remarkable indication of FEL saturation was not confirmed in the calculation. Farther improvement in beam confinement in the undulator will be required by the modification of the beam transport or focusing force in the undulator.

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