DESIGN AND NUMERICAL SIMULATION OF THz-FEL AMPLIFIER IN KYOTO UNIVERSITY

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Abstract

We have designed a relatively simple, compact and powerful THz-FEL (terahertz free electron laser) amplifier in Kyoto University. The target wavelength range of the amplifier is 150–340 µm, corresponding to 0.5-1.1 THz. The system consists of 1.6 cell photocathode radio frequency (RF) gun, THz wave parametric generator, focusing solenoid, transport line, and 120 cm long undulator with 30 periods. A start-to-end simulation in the institute of advanced energy Kyoto University has been conducted to estimate the performance of the designed system. Tracking of the electron beam from the photocathode RF gun up to the undulator entrance has been done using Parmela code while Genesis 1.3 code has been used to estimate the FEL interaction in the undulator. For feasibility study the FEL temporal distribution at resonance wavelength 186 µm was determined. The results show that 1250% amplification could be achieved in the resonance wavelength in the present design compared with the seed THz power. Details of the design and calculation conditions together with the performance test are presented in this paper.

INTRODUCTION

Terahertz free electron laser (THz-FEL) has futures of high peak power, a narrow spectrum bandwidth, and a high coherency compared with coherent synchrotron radiation THz sources [1]. Therefore, over the last two decades, there has been a significant interest in using THz technology as strong tool in different research and application fields. THz has attracted attention in the industrial applications because it can penetrate fabrics and plastics. In the security imaging, THz radiation can detect concealed weapons since many non-metallic and non-polar materials are transparent to THz radiation. THz spectra can be used to identify the compounds of explosives and illicit drugs as well. In the medical field, THz radiation can be used in diagnosis as it has make no damage on tissue or DNA and no health risk for scanning [2].

The principle of THz-FEL operation can be simply explained as a relativistic electron beam with optimum properties travelling through a transverse magnetic field in an undulator associated with an electric field from THz seed light. At a resonance condition, the passing electron beam transfer energy to the optical field and generate FEL light. The matching between the electron beam energy and the undulator parameters to generate FEL with specific wavelength can be determined from Eq. 1.

$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right). \quad (1)$$

$$K = \frac{eB_u\lambda_u}{2\pi mc}. \quad (2)$$

where λ_r is the FEL wavelength, λ_u is the undulator period, γ is the electron Lorentz factor, e is the charge of the electron, B_u is the peak magnetic filed in the undulator, m is the electron mass, and c is the speed of light. The target THz range in the present proposal is 0.5-1.1 THz tuned only by changing the electron beam energy

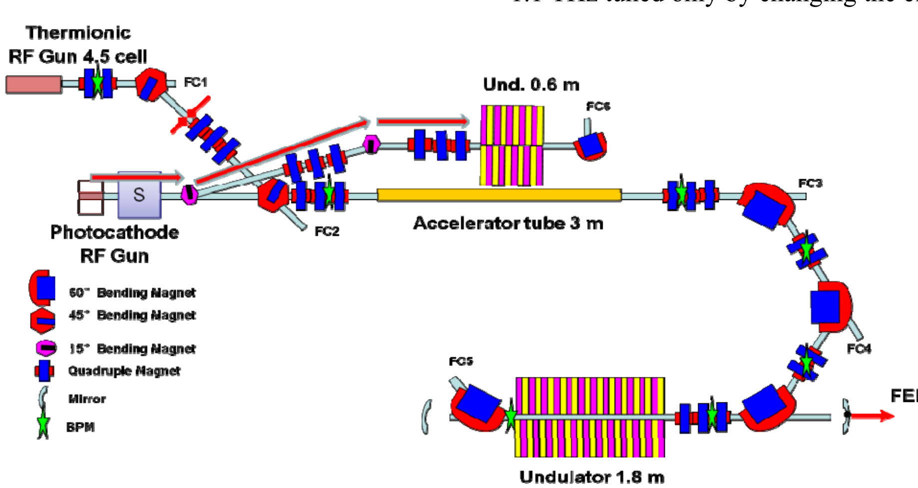

Figure 1: Schematic view of the KU-FEL facility configurations including the THz amplifier design.

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generated from the gun and fixing the undulator parameter.

In this paper, we are going to study the feasibility of designing a relatively simple and compact THz-FEL amplifier in Kyoto University and the expected performance is also discussed. The paper is organized into two main sections. The first one will describe the THz-FEL amplifier system principle and configuration as a part of Kyoto University machine. The second section will show a start-to-end calculation together with the performance test results.

THz-FEL AMPLIFIER IN KU-FEL

MIR-KU-FEL in Kyoto University

Before discussing the proposal of THz-FEL amplifier in Kyoto University, in this paragraph we will describe briefly the present MIR-KU-FEL (mid infrared Kyoto University free electron laser) configuration which the THz system will be adopted in and share. The recently upgraded system is consisting of S band (2856 MHz) thermionic RF gun with 4.5 cell driven by a 10-MW klystron for beam energy up to 9 MeV, a 3-m accelerator tube driven by a 20-MW klystron to deliver electron beam energy ranging from 18~40 MeV, a beam transport system, and 1.8 m Hybrid-type undulator with 52 periods. Figure 1 shows a diagram of KU-FEL facility configuration. The main target of this machine is to generate (5-20) μm light for energy science applications in Kyoto University [3,4].

THz-FEL Amplifier System

It is well known that FEL facility generally needs a huge space and very high cost. Therefore, a compact and low cost THz-FEL system can make a great contribution to develop and maximize the usage of THz light in many applications. The THz-FEL amplifier proposed in this paper consists of a 1.6 cell photocathode RF gun, a solenoid magnet for emittance compensation after the gun, transport line, a 120 cm undulator which amplifies THz light, and a THz seed light generator. The electron beam trajectory from the gun up to the final damp in the system is indicated with the arrows in figure 1. In the next paragraphs the system details shall be described.

The improved BNL photocathode RF gun with 1.6 cell [5], which manufactured in KEK, will be employed in the THz-FEL amplifier for electron production. The gun will be operated in the S band regime and will be driven from the same klystron used for the thermionic RF gun by sharing the RF power. Cesium telluride (Cs_2Te) material has been selected as cathode material in the system for the following reasons: Cs_2Te considered one of the highest materials quantum efficiency, less sensitive to gas exposure than other alkali semiconductors, it has reasonable life time compared with the available materials, it has a band gap energy of 3.2 eV, and electron affinity of 0.2 eV. Since Cs_2Te is almost blind to visible light, a drive laser of UV (ultraviolet) wavelength is needed to generate photoelectrons [6, 7]. A THz-wave parametric generator [8] with wide tunability will be used as a seed light to achieve a narrower spectrum than shot noise amplifier. Therefore, our original design adopted a parametric generator driven simultaneously by the UV laser used for the photoemission in the system [9]. The proposed laser system is designed to generate 300 bunches with micro-pulse energy of 1 μJ at wavelength of 266 nm. The laser system consists of a mode-locked $Nd:YVO_4$ laser as the oscillator, an acousto-optic modulator, a laser beam pointing stabilization system, a diode pumped Nd:YAG amplifier and 4^{th} harmonic generation crystals (for more details see [10]).

For beam focusing after the gun exit a solenoid magnet will be used to compensate the emittance growth. A transport line consists of achromatic dog-leg section and two matching triplet quadruples to adjust the beam waist at the undulator entrance. The angle of the bending magnets in the dog-leg section was selected as 15 degree. To realize and minimize the system size a short undulator of 120 cm length is assumed in the calculations. The undulator peak field, period length, period's number and K value are assumed to be 0.30 T, 0.04-m, 30 and 1.121 respectively. This configuration of the supposed system is designed based on the existing free space in the accelerator room for KU-FEL facility as shown in figure 1.

BEAM TRACKING CALCUALTION

Electron Beam Properties

The electron beam tracking from the photocathode RF gun to the undulator entrance has been done using Parmela simulation code [11]. During the simulation, 1 nC/bunch are assumed for the electron bunch extracted from the gun by illuminating the cathode with a laser whose rms transverse size and pulse duration are respectively 1.378 mm and 6.2 ps. To simplify the calculation, the Gaussian shapes are assumed for both the transverse (1 mm cut-off) and the longitudinal (20 ps cut-off) distribution.

FEL with a wavelength of 150-340 μm was fixed as light target in this calculations, then the beam energy required was estimated to be 4.5~ 7.0 MeV. To optimize the electron beam properties generated from the gun we conducted a scan for the field gradient in the gun against the laser injection phase for 50~70 MV/m and 30~70 degrees respectively. The results of the rms emittance, peak current and energy spread after the solenoid exit as a function of the laser injection phase at different gun fields are shown in figures 2 and 3 respectively.

The peak current, the energy spread and the emittance are the most important parameters which control the interaction between the electron beam and light in the undulator to generate FEL efficiently. In this meaning a high peak current with a low energy spread and a small emittance is preferable. It is clear from figures 2 and 3, that the minimum values of the rms emittance (~1 mm mrad) and the energy spread less than of 2% with a high peak current (100-130 A) can be obtained at the laser

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injection phase between 30~50 degree. The solenoid field was tuned in this calculation from 800~1600 gauss to optimize electron beam with low emittance. The results shown in this work have been done with 1247 gauss solenoid field.

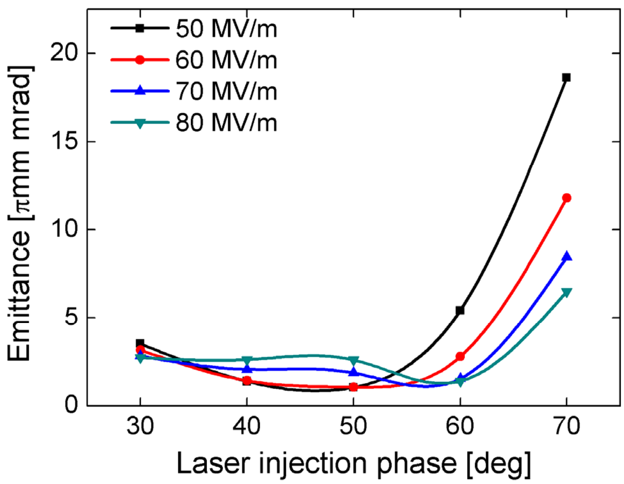

Figure 2: Emittance at the exit of the solenoid.

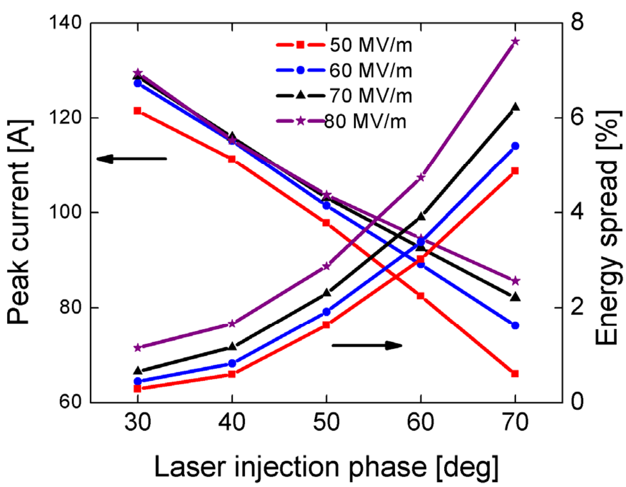

Figure 3: Energy spread and peak current at the solenoid exit.

Based on the above scanning, the electric field on the cathode surface 70 MV/m and 40 degree laser injection phase satisfy the minimum requirements of electron beam. These values will be used in the next calculation step to determine the electron beam properties at the undulator entrance. By using a Parmela code, we estimated the bunch length, the peek current, the energy, and the energy spread at the undulator entrance to be 4.26 ps (1.28 mm (rms)), 93.72 A, and 6.25 MeV, 0.89% respectively, for a bunch charge of 1.0 nC/bunch. These values will be used to estimate the FEL performance in the undulator in the next section.

SASE Radiation

For the interaction between the electron beam and the undulator field we used a 3D time-dependent simulation code Genesis 1.3 [12]. The electron beam parameters extracted from Parmela put together with the undulator parameters in Genesis and listed in Table 1. The entire power of seed light which was produced by THz-wave parametric generator was assumed to be 0.20 W.

The results of the simulation for the FEL power at the end of the undulator together with beam current are shown in figures. 4. It can be seen from the temporal distribution of FEL power at the timing of ~20 ps, the FEL gain amplified around 1250% compared to the seed THz power, but FEL saturation couldn't be achieved in present design. However, the amplification is high enough to perform some proof of principle experiments of THz-FEL amplifier.

Table 1: Electron Beam and undulator Parameters Used

Parameter	Value
Beam Energy	6.25 MeV
rms energy spread	0.87 %
rms pulse length	4.26 ps
Horizontal emittance ε_x	3.16 πmm mrad
Vertical emittance ε_y	1.72 πmm mrad
Horizontal beam size α_x	0.92 mm
Vertical beam size α_y	0.88 mm
Twiss parameter σ_x	1.88
Twiss parameter σ_y	1.19
Peak current	93.72 A
Resonance wavelength	185.94 μm
Undulator period length	40 mm
Number of periods	30
K value	1.12

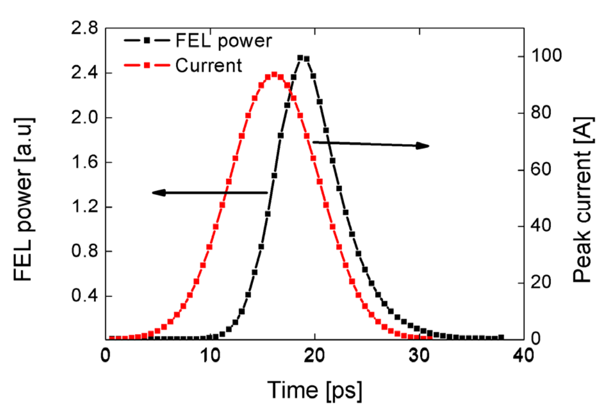

Figure 4: Temporal distribution of the FEL power and the beam current at the exit of undulator.

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CONCLUSIONS AND OUTLOOK

We have proposed and designed a relatively simple and compact THz-FEL amplifier. A start-to-end simulation has been performed to evaluate the original design and performance. Parmela and Genesis 1.3 simulation codes were used to track the electron beam from the cathode to the undulator entrance and determine the interaction between the electrons beam and undulator field respectively. The FEL gain was calculated to be 1250% based on the proposed design compared with the THz seed light. This amplification factor is high enough for performing some proof of principle experiments.

Further study is needed to determine the dependency of FEL power on the electron bunch length for higher FEL gain taking in consideration the slippage effect. The study of introducing different bunch charge, rms transverse size and pulse duration for the pump laser are also foreseen. Study of the dark current in the proposed system is needed. More simple and compact THz-FEL amplifier design still needed for maximizes the THz-FEL applications.

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