MIR-FEL TUNABLE RANGE AT KYOTO UNIVERSITY

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Abstract

A mid-infrared free electron laser (MIR-FEL) facility (KU-FEL: Kyoto University Free Electron Laser) has been constructed for energy science in Institute of Advanced Energy, Kyoto University. The first laser amplification at 12 μm was observed in March 2008. A beam loading compensation method with an RF amplitude control in the thermionic RF gun was used to qualify the electron beam. A developed feedforward RF phase control was applied to stabilize the RF phase shifts as well as RF detuning method. As a result FEL gain saturation at 13.2 μm has been achieved for the first time in May 2008. With varying the beam energy under the fixing K-value (0.99) condition of the undulator, the tunable range of KU-FEL was estimated numerically to design the MIR-FEL beamline for application purposes. The results indicated that the tunable range could cover from 5-13.2 μm. Experimental data for supporting the numerical calculation has been under taken.

1. Introduction

An IR-FEL is a powerful tool to investigate biological and chemical reactions, because tunable coherent light can selectively induce a specific molecular reaction. For this purpose a mid-infrared free electron laser facility (KU-FEL) has been constructed at the Institute of Advanced Energy, Kyoto University [1]. The construction of the facility was finished in 2006 [2]. We started FEL oscillation experiments in 2007 and succeeded in the first lasing at a wavelength of 12.4 μm in March 2008 [3]. FEL gain saturation at 13.2 μm has been achieved for the first time in May 2008. In this paper, we will report on the numerical calculation and the conditions of the tunable rang estimations in KU-FEL.

2- KU-FEL system

The KU-FEL system consists of an S-band 4.5-cell thermionic RF gun driven by a 10 MW klystron, a 3 m accelerator tube driven by a 20 MW klystron, a beam transport system, and a Halbach type undulator of 1.6 m. Fig.1 shows a schematic drawing of the KU-FEL system. A LaB_6 thermionic cathode of 2 mm diameter was employed to produce a high-brightness electron beam. A transverse magnetic field of about 10 G on the cathode surface was applied to divert backstreaming electrons [4]. The strength of the magnetic field was chosen so that backstreaming electrons with energy lower than about 300 keV could be diverted well while a transverse kick to the accelerated electron could pass through the 8 mm iris of the RF gun. Although the transverse magnetic field partially minimized the cathode heating effect owing to backstreaming electrons, we observed that cathode surface temperature still increased during the macropulse duration of 2-3 μs. Then we applied amplitude-modulated RF pulses to the RF gun to compensate for the beam loading effect [5]. As a result, the energy degradation in the thermionic RF gun due to backstreaming electrons was dramatically improved and an electron beam pulse of approximately 4.5 μs long with a 375 mA average current was successfully extracted from the gun.

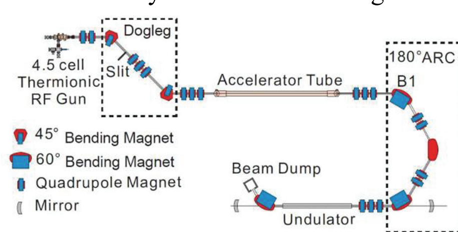

Figure 1. Schematic drawing of KU-FEL.

An achromatic transport system (dogleg section in Fig.1) consists of a 45° bending magnet and an energy slit, three quadrupole magnets and another dipole magnet, and it serves as an energy analyzer [6]. The energy slit was set to select the electron beam of about 3% energy spread. After energy slit, the average current reduced to around 100 mA and the increase of beam current during the macropulse due to the back-bombardment effect is still remained. An S-band 3 m accelerator tube accelerates the electron beam up to 40 MeV using a 20 MW RF power. The beam loading effect in the tube was also compensated by the amplitude modulation method [7].

The 180° arc in Fig.1 designed for a bunch compressor [6] was tuned to obtain a high peak current of the electron beam. The bunch length was estimated from measured FEL gain and other beam properties as around 500 fs. Thus the micropulse peak current in the FEL saturation experiment was about 38 A. Two triplet quadrupoles located on both sides of the 180° arc worked as a beta-match component between the linac and the undulator. A planar-type undulator, which was used for the saturation experiment in the collaboration between FELI and the University of

Tokyo [8], was used. The undulator length is 1.6 m, the period is 40 mm, the number of periods is 40 and the undulator parameter K-value is varied from 0.99 to 0.17 by changing the gap of the undulator. The optical resonator consists of a pair of gold-coated Cu mirrors with 99.04% reflectivity, the upstream mirror of which has a coupling hole of 2 mm ϕ. The horizontal and vertical normalized emittances at the undulator were measured by a tomographic method [9].

3. Results and discussion

The tunable range of KU-FEL was estimated numerically by changing the beam energy from 18.5 MeV to 42 MeV under a fixing *K*-value of undulator of 0.99. In this calculation, transverse emittance, beam size, and Twiss parameters α_x, α_y were optimized to obtain the maximum FEL gain using a 3D FEL simulation code, GENESIS [10]. It should be noted that the simulation code was modified to treat the round-trip development of the FEL, the rapid increment of the electron beam current, the diffraction loss with precise geometry of the vacuum chamber of the optical cavity system [11], and reflection loss of cavity mirrors. The ramped peak current from 20 to 40 A are also used as the fixed parameter. The realistic geometry of KU-FEL optical cavity shown in Figure 2 was taken into consideration in the calculations.

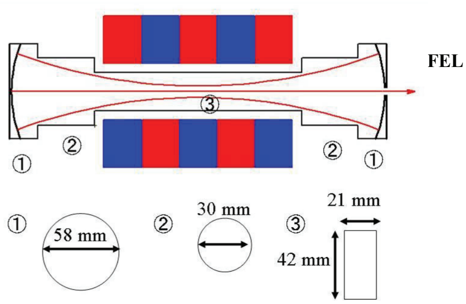

Figure 2, Geometry of the optical cavity of KU-FEL.

The measured macro-pulse width for the FEL gain saturation experiment of the entire electron beam was 5.5 μs, however the time duration with constant beam energy was 4.5 μs. In the present calculations we used 4.5 μs for macro-pulse duration. The relation between the relative energy spread and the number of periods in the undulator in high gain condition given as $\Delta E/E \leq 1/2N$ [12]. The measured energy spread at the exit of the RF gun and the accelerator tube for energies 8.2 and 24.2 MeV were 240 keV and 250 keV respectively. It means that no significant energy spread widening occurred during acceleration in accelerator tube. Figure 3, shows the energy spread at the exit of the RF gun. The relative energy spread required to have high gain for efficient amplification of FEL in KU-FEL is $\Delta E/E$=0.0125 [13]. The observed relative energy spread at the exit of accelerator tube at the range of 24 MeV and 39 MeV was almost the same and less than 0.0125. Moreover, numerical simulation also supported the experimental result, in this meaning we expects high FEL gain in this energy range. The absolute values of the energy spread and the bunch length were fixed as 240 keV in FWHM and 500 fs respectively. The electron beam parameters which used in the tunable range calculations, the beam size, Twiss parameters and emittance are listed in table 1.

Table 1 Electron beam parameters used in simulation.

Energy spread (FWHM) keV	240
Bunch length (fs in rms)	500
Macropulse length (μs)	4.5
Horizontal Emittance $\varepsilon_{n,x}$ mm-mrad	4
Vertical Emittance $\varepsilon_{n,y}$ mm-mrad	12
Horizontal Beam size σ_x mm	0.49
Vertical Beam size σ_y mm	0.34
Twiss parameters α_x	2.55
Twiss parameters α_y	-0.10

The parameters of undulator were fixed as the period length 40 mm, number of periods 40 and *K*-value was 0.99.

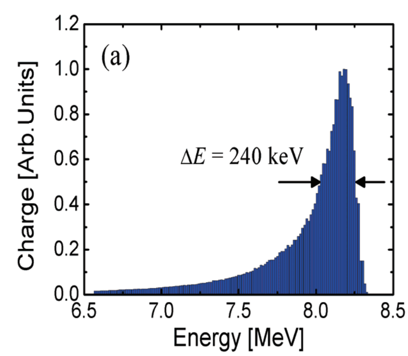

Figure 3, the energy spread at the exit of the RF gun.

Figure 4, shows the relation between the intra-cavity power and the wavelength at the end of the macro-pulse. The calculations indicated that the maximum value of the intra cavity power is 10^8 W has been achieved at 8 μm.

The optical power below and over the range 5-13.2 μm rapidly drops as shown in figure 4. If electron beam with same properties, which used in the tunable range calculations, are used for FEL lasing, the gain gets smaller when the wavelength gets shorter considering the relation between the gain and wavelength [14]. However, relative energy spread $\Delta E/E$ gets smaller with assumption of constant absolute energy spread ΔE when the beam energy gets higher (it means shorter wavelength). In this case, contribution of energy spread narrowing to FEL gain enhancement is more significant than that of wavelength shortening. Thus the gain gradually increases when the wavelength is varied from 13 to 8 μm. For

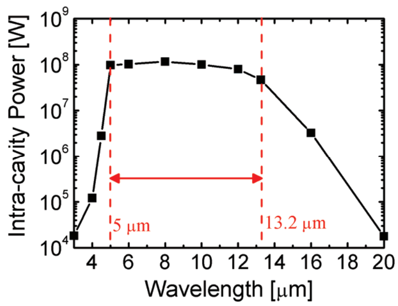

Figure 4, the relation between the output power and the wavelength.

shorter wavelength than 8 μm, the effect of wavelength shortening gets larger and gain rapidly decreases as shown in figure 5.

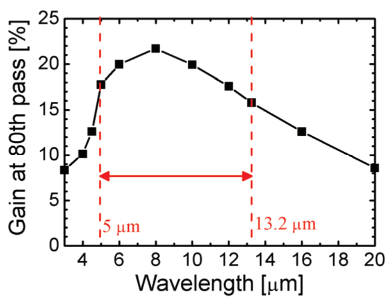

Figure 5, the relation between the FEL gain at 80th pass and the wavelength.

Figure 5, shows the relation between the wavelength and the FEL gain at 80th pass, from the figure the gain increase with decreasing the wavelength from 13.2 to 8 μm, and rapidly decreases with decreasing the wavelength less than 8 μm. The lasing experiments in KU-FEL confirmed the tunable range between 12-13.2 μm. The tunable range between 5-12 μm has been under taken.

4. Conclusion

By numerical simulation, the tunable range of KU-FEL was predicted as 5-13 μm with fixed K-value at 0.99 with energy spread 240 keV. The measured wavelength in KU-FEL confirmed the range 12-13.2 μm. Lasing experiment at different wavelength from above range and optimization of operational parameter of KU-FEL driver linac will be performed to demonstrate the wavelength tunability of the KU-FEL in the near future.

5. References

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