Nuclear Instruments and Methods in Physics Research A 475 (2001) 47–50

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

www.elsevier.com/locate/nima

First lasing of the KAERI compact far-infrared free-electron laser driven by a magnetron-based microtron

Young Uk Jeong[a,*], Byung Cheol Lee[a], Sun Kook Kim[a], Sung Oh Cho[a], Byung Heon Cha[a], Jongmin Lee[a], Grigori M. Kazakevitch[b], Pavel D. Vobly[b], Nicolai G. Gavrilov[b], Vitaly V. Kubarev[b], Gennady N. Kulipanov[b]

[a] *Korea Atomic Energy Research Institute, P. O. Box 105, Yusong, Taejon 305-600, South Korea*
[b] *Budker Institute of Nuclear Physics, Lavrentyev ave. 11, 630090 Novosibirsk, Russia*

Abstract

The KAERI compact far-infrared (FIR) free-electron laser (FEL) has been operated successfully in the wavelength range of 97–150 μm. It is the first demonstration of FEL lasing by using a magnetron-based classical microtron. We developed a high precision undulator consisting of 80 periods, with each period being 25 mm. The field strength of the undulator can be changed from 4.5 to 6.8 kG with an amplitude deviation of only 0.05% in r.m.s value. The kinetic energy of the electron beam is 6.5 MeV. The average current and pulse duration of the electron beam macropulses are 45 mA and 5.5 μs, respectively. The measured power of the FEL with the electron beam parameters was more than 50 W for a FIR macropulse having a duration of 4 μs. The spectral width of the FEL was measured to be 0.5% of the central wavelength. The FEL system, aside from the racks for the controlling units, is compact enough to be located inside an area of $3 \times 4\,\mathrm{m}^2$. © 2001 Elsevier Science B.V. All rights reserved.

PACS: 41.60.Cr; 52.75.Ms

Keywords: Lasing; Free-electron laser; Microtron; Far infrared; Compact FEL

1. Introduction

There is an increasing demand for tunable sources in the wavelength range of far infrared (FIR) for applications in solid-state physics, plasma physics, chemistry, bio-medical research, and surface science [1–3]. To make the free-electron laser (FEL) a potent source for such applications, its size and cost should be within the means of an individual research laboratory. Progress has been made toward a compact FIR FEL using radio frequency (RF) guns as the electron beam source [4,5]. The compactness and beam quality of such an accelerator, having an energy range of several MeV, are crucial factors for FEL applications. A microtron using an RF generator for a magnetron has several noticeable advantages in cost, size, beam quality and operational convenience.

We have developed a compact FIR FEL driven by a magnetron-based microtron [6,7]. The first lasing in the wavelength range of 97–150 μm was

*Corresponding author. Tel.: +82-42-868-8342; fax : +82-42-861-8292.

E-mail address: yujung@kaeri.re.kr (Y.U. Jeong).

0168-9002/01/$ - see front matter
PII: S0168-9002(01)01533-9

achieved at the end of 1999, after successful results with the frequency stabilization of the RF, a high-performance undulator, and a complex optical resonator with a high coupling ratio between electron beam and radiation mode. The lasing results of the FEL are shown and discussed in this report, with a brief description of the facility.

2. Microtron and beam line

The schematic layout of the FEL system is shown in Fig. 1. The main parameters of the system are listed in Table 1. The electron energy from the microtron is 6–7 MeV depending on the magnetic strength of its main magnet. The macropulse duration of the electron beam is 5.5 μs and the pulse current is up to 70 mA. The microtron is composed of a magnetic-vacuum system, an RF system, and a modulator for the magnetron. The volume of the total system is only 2 m^3. Details on the microtron are described in Ref. [8].

The RF system of the microtron was designed to stabilize the magnetron frequency. The stabilization of the magnetron due to the frequency pulling effect was realized by a short-length RF line and by allowing the reflected wave from an RF accelerating cavity to reach the magnetron. The length of the RF line from the magnetron to the RF cavity is approximately 1 m and the isolation ratio for the reflected wave is <15 dB at the RF pulse power of 2 MW. The long-term fluctuation of the RF frequency is kept within the range of 40 kHz ($\Delta f/f_0 \sim 10^{-5}$) by keeping the temperature of the RF cavity constant to an accuracy of 1°C. The measured deviation of the RF frequency

Table 1
Main parameters of the KAERI FIR FEL

Electron beam	
Electron beam energy	6–7 MeV
Macropulse current	40–50 mA
Horizontal emittance	3.5 mm mrad
Vertical emittance	1.5 mm mrad
Energy spread	0.3–0.4%
Beam size at undulator entrance (FWHM)	2.1 mm × 0.6 mm
Macropulse duration	5.5 μs
Micropulse repetition frequency	2.8 GHz
Undulator (planar electromagnet)	
Period (Number of periods)	25 mm (80)
Peak magnetic Induction	4.5–6.8 kG
Gap	5.6 mm
Resonator	
Cavity length	2781 mm
Cylindrical mirror	$R = 3000$ mm
Waveguide gap	2.0 mm
Waveguide length	2778 mm
Radiation wavelength	97–150 μm

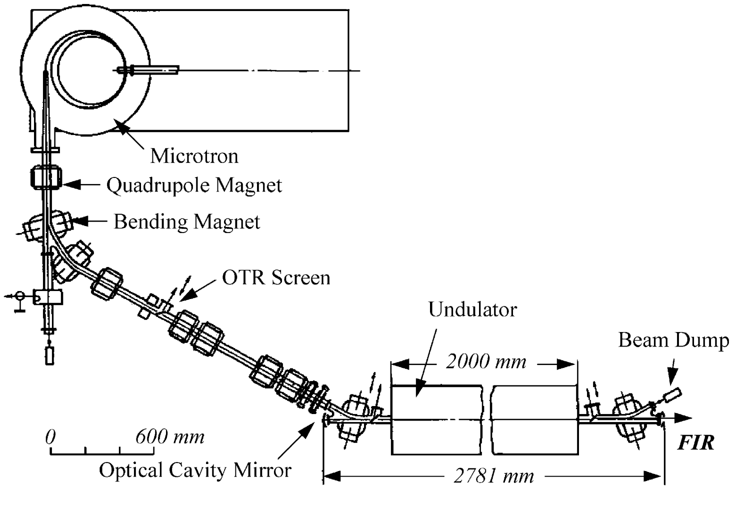

Fig. 1. Schematic layout of the KAERI compact FEL.

during the pulse is $<150\,\text{kHz}$ in the case of the optimized beam parameters for the laser. This value is much less than that measured for the magnetron itself. We have investigated the effect of the measured frequency fluctuations on the lasing process by simulation. The result shows sufficient gain of the FEL oscillation up to saturation power within the pulse width of $5\,\mu\text{s}$.

Electrons accelerated by the microtron are transported through the beam line with three bending magnets and six quadruples. The beam line is used for matching the input condition of the electron beam to the undulator for optimum laser operation. The beam line also includes a current transformer and an optical transition radiation (OTR) screen for electron beam diagnostics. An OTR screen with beam optics is being used to measure the Twiss parameters of the electron beam.

3. Undulator and optical cavity

The main issues concerning the design of a microtron-driven FIR FEL are the maximization of the FEL gain and the minimization of the gain reduction factors, including the resonator losses. To obtain enough gain for FEL oscillation, we have focused on developing a strong and high precision electromagnet undulator with an optimized length. The total length of the undulator is 2 m, containing 80 periods of length 25 mm. The configuration of the undulator is described in Ref. [9]. In this undulator, permanent magnets are used to reduce the saturation in iron poles. The magnetic field strength can be tuned from 4.5 to 6.8 kG by changing the current on the main coils. Deviation of the field amplitude from pole to pole all along the undulator was measured at the extremely low value of 0.05%. We have improved the accuracy of the undulator with a modular pole structure. This new structure makes fabrication and assembly much easier, as well as significantly reducing the cost and time for construction of the undulator.

The resonator of the FEL comprises a confocal scheme in the horizontal plane, with cylindrical mirrors and a parallel-plate waveguide with a gap of 2 mm in the vertical plane to increase the coupling between the electron beam and the radiation mode. The cross-section of the waveguide is $2\,\text{mm} \times 30\,\text{mm}$. The 2780 mm long waveguide is centered to within 0.1 mm (height fluctuations). The diameter of the electron beam envelope in the vertical plane of the undulator is estimated to be $<1\,\text{mm}$ and the electron beam can be transported through the waveguide without loss. The out coupling mirror has a 0.7 mm diameter hole. The coupling ratio is approximately 2% of the intracavity power. The alignment accuracy and stability of the mirrors are better than 0.05 mrad. The electron beam is also aligned to the axis of the optical resonator with two OTR screens located at both ends of the undulator. The positioning accuracy and stability of the electron beam is approximately 0.1 mm. These accuracies satisfy the requirement of the confocal and waveguide mode resonator for lasing.

4. Lasing results

Two liquid helium cooled Ge : Ga detectors have been used to measure the power and the temporal evolution of the FIR radiation [10]. One of the detectors was calibrated at the wavelength of $118\,\mu\text{m}$ by using a stable water-vapor laser.

Fig. 2 shows a typical waveform of the FEL oscillation. A temporal shape of the electron beam current is shown for comparison. The build-up time for the oscillation is $<1.5\,\mu\text{s}$. The power of the FEL was stable and the fluctuation of the

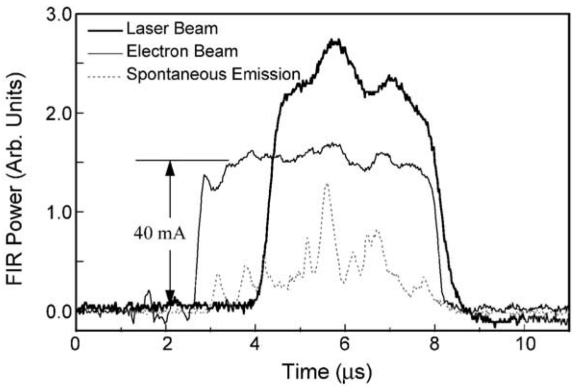

Fig. 2. Typical waveform of the FEL oscillation (solid line) and the spontaneous emission (dotted line) at a wavelength of $118\,\mu\text{m}$.

power is $<1\%$ in r.m.s value. The loss of the radiation in the resonator was measured to be 13% for a wavelength of 120 μm and is in good agreement with the calculated value. The calculated value of the net small-signal gain ranges from 15% to 25% depending on the radiation wavelength. The waveform of the spontaneous emission is shown in Fig. 2 as a dotted line. It should be noted that the power ratio between the laser and the spontaneous emission is more than 3000. The spontaneous emission power of the FEL is 100 times stronger than the calculated value. It is attributed to the coherent effect induced by the modulated structure of the electron beam micropulses [11,12]. The measured power of the spontaneous emission tends towards a quadratic dependence on the electron-beam current. The power enhancement of the spontaneous emission contributes to reducing the build-up time of the oscillation. The fluctuation of the laser pulse width is approximately 1 μs, which can be explained by the power fluctuation of the spontaneous emission.

Laser power dependence on the resonator length was measured for several wavelengths and it is shown in Fig. 3. The macropulse power of the laser was measured by using a pyroelectric detector. It was approximately 50 W for a wavelength of 120 μm. The calculated power from the simulation was approximately 80 W. The measured results of the power and dependence on the cavity detuning are in good agreement with those of the simulation.

Fig. 4 shows a spectrum of the laser beam measured using a Fabry–Perot spectrometer. The

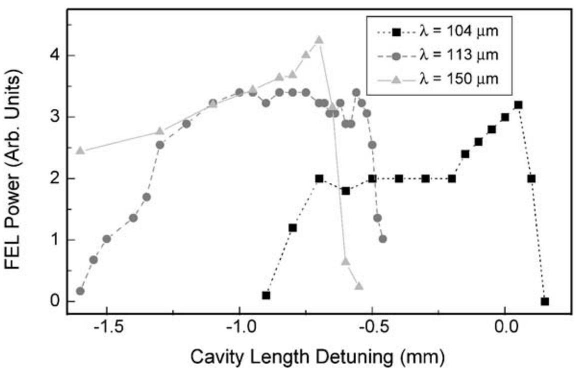

Fig. 3. Laser power dependence on the resonator length at wavelengths of 104, 113, and 150 μm.

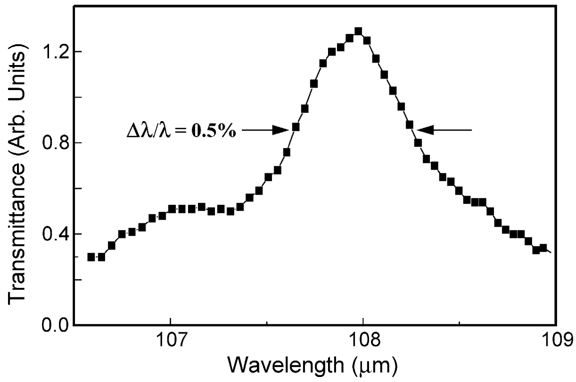

Fig. 4. Measured spectrum of the laser beam by using a Fabry–Perot spectrometer at a wavelength of 108 μm.

resolving power of the spectrometer is approximately 1000. The measured linewidth of the spectrum is $0.5\,\mathrm{cm}^{-1}$, $\Delta\lambda/\lambda = 0.5\%$, for a wavelength of 108 μm, and the Fourier transform limit associated with the laser micropulse is estimated to be $0.2\,\mathrm{cm}^{-1}$. The linewidth of the spectrum can be increased up to 1.2% by increasing the gain with a longer wavelength.

References

[1] S.J. Allen, Nucl. Instr. and Meth. B 144 (1998) 130.
[2] D. Dlott, M. Fayer, IEEE J. Quantum Electron. QE-27 (1991) 2697.
[3] E.V. Alieva, et al., Phys. Solid State 40 (1998) 213.
[4] I.S. Lehrman, et al., Nucl. Instr. and Meth. A 393 (1997) 178.
[5] J. Schmerge, et al., IEEE J. Quantum Electron. QE-31 (1995) 1166.
[6] R.R. Akberdin, et al., Nucl. Instr. and Meth. A 405 (1998) 195.
[7] Jongmin Lee, et al., Nucl. Instr. and Meth. A 407 (1998) 161.
[8] G. Kazakevich, et al., Compact Microtron Driven by a Magnetron as an Injector of the FIR Free Electron Laser, Presented at the 22nd International FEL Conference, Durham, USA, August 2000.
[9] Y.U. Jeong, et al., Nucl. Instr. and Meth. A 407 (1998) 396.
[10] V. Kubarev, et al., Proceedings on the Fourth Asian Symposium on FELs, Taejon, Korea, 1999, p. 369.
[11] Y.U. Jeong, et al., Phys. Rev. Lett. 68 (1992) 1140.
[12] G. Kazakevich, et al., Nucl. Instr. and Meth. A 475 (2001) 599, these proceedings.