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Section A

Design and construction of a far-infrared free-electron laser driven by a microtron

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Abstract

A far-infrared free-electron laser driven by a microtron has been developed. The free-electron laser system is continuously tunable in the wavelength range from 30 to 50 μm. The energy of the electron beam is 7.5 MeV at maximum. The pulse duration and the repetition rate of the macropulses are 5 μs and 10 Hz, respectively. The average current in a macropulse is 50 mA. In order to get high enough gain of the free electron laser, we developed a long electromagnetic undulator with high magnetic field strength. The period of the undulator is 12.5 mm and the number of the periods is 160. The peak magnetic field of the undulator is tunable from 4 to 6 kG at a fixed gap distance of 5 mm by changing the current through the electromagnet. More than 99% of the electron beam passed through the undulator. The results of numerical simulation show that the measured parameters of electron beam are good enough for lasing. Critical issues in lasing of the free-electron laser are discussed. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

In the far-infrared (FIR) region of wavelength, the free-electron laser (FEL) is a very promising tool for scientific research because, in this region of wavelength, the non-laser sources are weak and the use of conventional laser sources is very limited. Many applications of the FIR FEL are expected in chemistry, surface science, solid-state physics, biophysics, plasma diagnostics, etc. [1].

A far-infrared (FIR) free-electron laser (FEL) driven by an 8 MeV conventional microtron is under development for the purpose of scientific applications of advanced FIR radiation. The microtron has many advantages over radio-frequency (RF) linear accelerators: compactness,

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cost-effectiveness, high beam quality, easy operation and maintenance, etc. One drawback of the microtron as a driver of FELs is the fact that its peak current is intrinsically low. The electron beam current from the microtron is limited because the size of the emitting cathode is limited and many bunches of electrons with different energies pass through the same acceleration cavity simultaneously. Several efforts to get FEL oscillations by using a microtron have been focused on increasing the peak current of the electron beam [2,3].

Since the quality of the electron beam in the KAERI microtron is very good, we can use a long undulator in order to get high FEL gain. The small-signal gain of an FEL is linearly proportional to $I_p N_u^3$, where I_p is the peak current and N_u is the number of undulator periods. The maximum number of undulator periods that we can use in an FEL is inversely proportional to the energy spread ($\Delta E/E$) of the electron beam as below:

$$N_{\max} \approx \frac{1}{2}\left(\frac{E}{\Delta E}\right).$$

In general, the energy spread of the electron beam from RF linear accelerators is 1%. Thus, the maximum number of the undulator period is about 50. The energy spread of an electron beam from a microtron is less than 0.3%, and thus the maximum number of undulator periods is 160.

In addition to the factors such as peak current, beam quality, and undulator length, it is also very important to reduce the loss in the optical cavity. We designed an optical cavity such that the round-trip loss is less than 10%. According to numerical simulations using the measured beam parameters, the peak power of the FIR FEL is of the order of 10 kW.

2. Microtron and beamline

Fig. 1 shows a schematic diagram and Fig. 2 shows a photograph of the FIR FEL system. The main parameters are listed in Table 1. The dimension of the system is small enough (3 m × 5 m) to be installed inside a laboratory. The microtron is a cyclic electron accelerator with a constant accelerating frequency and a constant transverse magnetic field. The electron beam is generated from a thermionic cathode, which is located at a distance of 29.5 mm from the center of the RF accelerating cavity. Type I injection of the electron is used [4]. The cathode material is LaB_6 and its diameter is 2.5 mm. The maximum number of passes of the electron beam through the RF cavity is 12. The

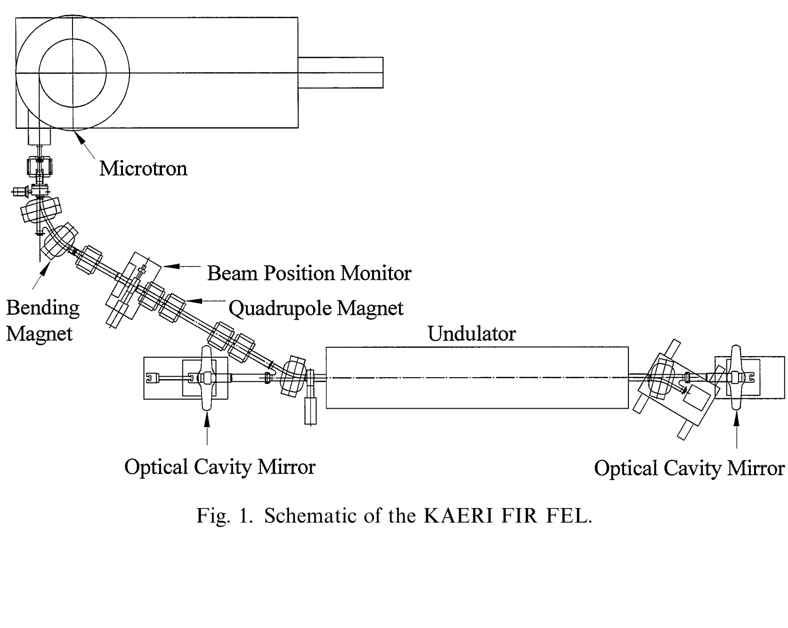

Fig. 1. Schematic of the KAERI FIR FEL.

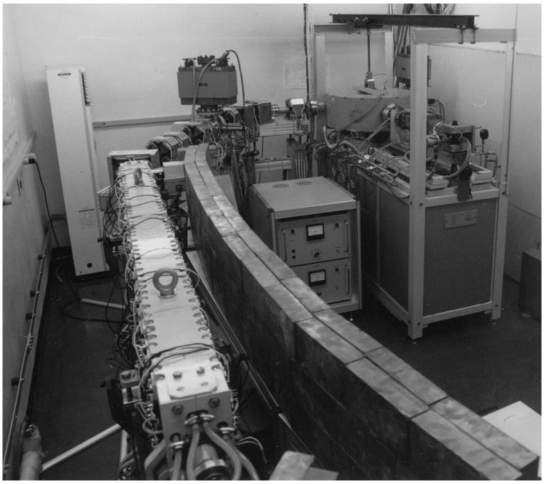

Fig. 2. Photograph of the KAERI FIR FEL.

Table 1
Design parameters of the FIR FEL

Radiation	Wavelength	30–50 μm
	Micropulse duration	~ 20 ps
	Macropulse duration	5 μs
	Repetition rate	10 Hz max.
	Peak power	10 kW
	Average power	0.1 W
Electron beam	Energy	7.5 MeV max.
	Macropulse current	50 mA
	Emittance	1 mm mrad
	Energy spread	0.3%
Undulator	Period	1.25 mm
	Number of periods	160
	Length	2 m
	K value	0.4–0.7

energy gain per pass is 500–700 keV according to the RF power. The frequency and the peak power of the RF field is 2.8 GHz and 2.5 MW, respectively. The diameter of the microtron magnet is 0.7 m. The strength of the transverse magnetic field is about 1.1 kG and its uniformity is within 0.1%. The beam extraction channel includes a ferromagnetic channel with field-distortion compensators near the last orbit. The micropulse pulsewidth of the electron beam is 10–20 ps. The peak current of the micropulse is about 1 A.

One of the important parameters in the design of the microtron is the capture coefficient: the ratio of the number of electrons captured (accelerated) by the acceleration field to the number of electrons generated from the cathode surface [5]. The higher the capture coefficient, the higher the peak current of the electron beam. Fig. 3 shows the calculated capture coefficients for different positions of the cathode and for different values of the acceleration field. It is shown that the optimal position of injection for maximum capture coefficient is sensitive to the strength of acceleration field. We can see that the RF power should be stable within ~ 3%. Many simulations show that the optimal position of injection is 29.5 mm from the center of the cavity.

Another important parameter is energy spread of the electron beam. There are two sources of energy spread; one is the intrinsic energy spread due to different phase angle of capture, and the other is the energy spread due to instability of the RF power during a pulse. The intrinsic energy spread depends on the strength of acceleration field and the position of injection. There are two sources of the instability of RF power; one is the instability of the RF generator and the other is change of emission current during a pulse. Observations show that the emitted current at the end of a pulse is ≈ 30% higher than that at the beginning. It is because a part of the electrons come back to the cathode and heat it, so its temperature and emission current are increased too. It means that there is a possibility that the acceleration field changes according to the change in the emission current. Thus, it is possible that the energy of the electron beam changes during a pulse, which is an undesirable situation for FEL lasing.

Fig. 4 shows the calculated energy spectrum of the electron beam. The energy spread is almost independent of the position of injection and is 20 keV (0.3% of the e-beam energy). This energy spread is calculated for the entire region of stable operation, and thus in a real situation where the operation region can be smaller, the energy spread can become smaller than the above value. Further simulations show that the stabilization of RF power in the cavity leads to a dramatic improvement of beam parameters, including the energy spread.

The beamline is composed of three 30° bending magnets, six quadrupole magnets, two beam profile

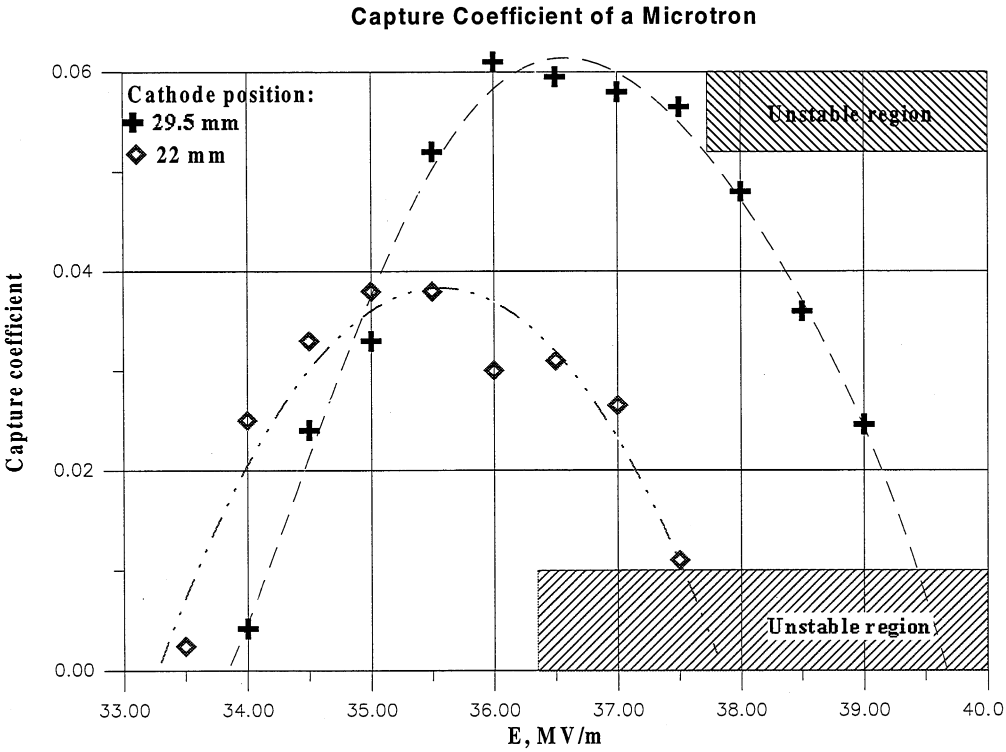

Fig. 3. Capture coefficients of the electron beam at the RF cavity.

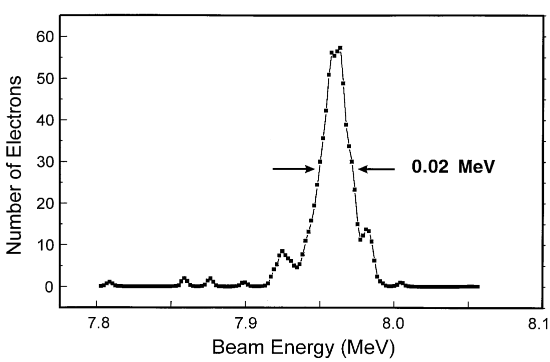

Fig. 4. Energy spectrum of the electron beam.

monitors, one current transformer, and one vacuum pump. Each bending magnet with parallel face has one main coil and one steering coil. The length of the bending magnet is 131.8 mm and the gap is 40 mm. Each quadrupole magnet with a parallel face has one main coil and one steering coil. All the power supplies of the magnets are computer remote controlled by the computer. The position and the distribution of the electron beam are monitored by using an optical transition radiation (OTR) screen. The OTR screen consists of two tantalum plates with 0.1 mm thick perpendicular slits such that scanning of the profile is possible. The upper plate of the OTR screen is covered by an aluminum foil. The image of the electron beam is captured by a CCD camera.

Parameters of the electron beam are measured by measuring the change of transverse distribution of the electron according to the change of focusing forces of the quadrupoles [5]. The size of the beam is 5 mm × 1.5 mm. The measured emittance of the electron beam is less than 1 mm mrad. The energy spread ($\Delta E/E$) of the electron beam is less than 0.3%.

3. Undulator and beam transport

A permanent-magnet-assisted electromagnet undulator has been developed [6]. In general, permanent-magnet undulators have a complex mechanical system for the tuning of the gap distance, and this increases the cost of the undulator. In a new concept of CW electromagnet undulator, the alternating magnetic field is induced by the electric coils wound around an assembly of alternating magnetic poles made of iron. The magnetic field connection between neighboring magnetic poles is protected by the use of a permanent magnet. The design has the merits of easy fabrication, operation, and maintenance. Since the gap is fixed, the mechanical structure of the undulator is simpler than that of the Halbach-type undulators. The magnetic field can be changed very quickly so that the wavelength of the FEL can be changed in a very short time. Even though fluctuation in the magnetization of the permanent magnet blocks is about 5%, the resulting fluctuation of the magnetic field is only 1%. Fine adjustment of the field distribution is done by using correction coils and shimmer magnets. A DC power supply provides the undulator a current of 1.7 kA. The fluctuation of the current is less than 0.1%. More than 99% of the incident electron beam passed through the undulator.

4. Optical cavity

An optical cavity for the FIR FEL has been designed and is under fabrication [7]. Due to the small gap distance of the undulator and large diffraction of the radiation, the optical cavity has quasi-optical geometry. In the horizontal direction, it is a free-space mode resonator with two confocal cylindrical mirrors. In the vertical direction, it is a bounded-mode resonator with a metallic waveguide. Fig. 5 shows the cross-sectional view, top view, and horizontal view of the optical cavity. The cross-sectional dimension of the waveguide vacuum channel is 20 mm × 3.6 mm. The material of the waveguide vacuum channel is aluminum. The inner surface of the channel is finely polished such that it works as a waveguide of FIR radiation. Output coupling of the radiation is done by using a hole located at the center of the mirror.

The material of the vacuum window is KRS5, whose transmittance is 85% at the wavelength of 30–40 μm and less than 50% at 50 μm. The window is located outside the optical resonator such that the absorption due to multiple passes of radiation inside the resonator is avoided. The most significant loss occurs due to the finite horizontal dimension (20 mm) of the channel. The absorption loss in the waveguide surface is estimated to be 0.2%.

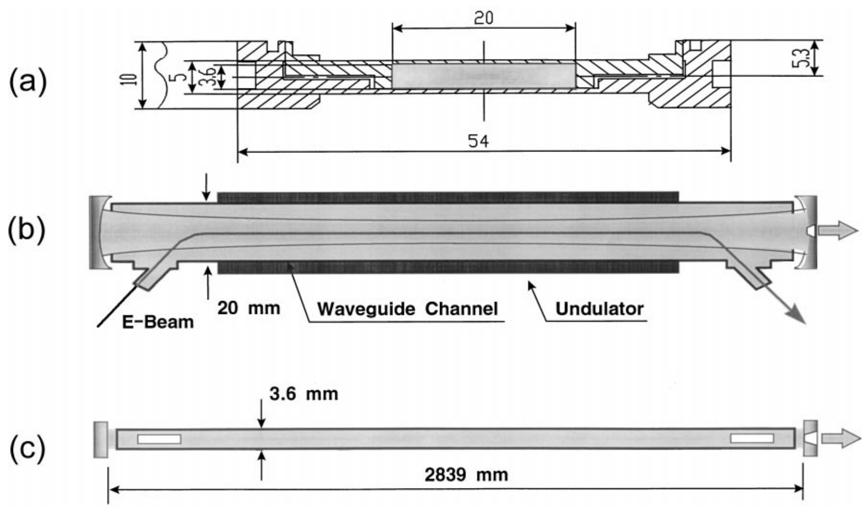

Fig. 5. Schematic of the optical cavity: (a) cross section; (b) top view; and (c) horizontal view.

Total round-trip loss of the radiation in the optical cavity is less than 10%.

We have developed a one-dimensional simulation code for the estimation of the optical power from the FIR FEL [8]. The simulation code includes a short-pulse effect of the electron beam. According to the simulations, the peak optical power from the FIR FEL is expected to be 10 kW.

5. Summary

The FIR FEL being developed at KAERI is designed to be continuously tunable over the wavelength range from 30 μm to 50 m. The use of a microtron makes the system very compact such that the FEL can be installed in a small laboratory. In order to get a high gain FEL we used a high field, long undulator. More than 99% of the incident electron beam passed through the undulator. The simulation using the measured parameters of the electron beam shows that the FEL gain is high enough.

Acknowledgements

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