УДК 538.9
PACS number 41.60.Cr, 42.25.Hz, 42.25.Kb

Y. U. Jeong [1], G. M. Kazakevich [2], S. H. Park [1], K. Lee [1], J. Mun [1], K. H. Jang [1], J. Y. Lee [1], J. Sunwoo [1], K. N. Kim [1,3], B. C. Lee [1], Y.-H. Cha [1], H. Cha [1], D. H. Kim [4], B. H. Cha [1]

[1] Korea Atomic Energy Research Institute
1045 Daedeok Street, Yuseong, Daejeon 305-353, Korea
E-mail: yujung@kaeri.re.kr

[2] Budker Institute of Nuclear Physics, SB RAS
630090, Lavrentiev av. 11, Novosibirsk, Russia

[3] Kongju National University
182 Shingwan,Gongju, Chungnam 314-701, Korea

[4] Hanbat National University
San 16-1, Duckmyoung, Yuseong, Daejeon 305-719, Korea

DESIGN STUDY OF A TABLE-TOP THZ FREE-ELECTRON LASER FOR SECURITY INSPECTION

We have designed a table-top terahertz (THz) free electron laser (FEL). The main issue of the FEL design is to decrease radiation losses at a FEL resonator except outcoupling ratio. Also reducing the number of undulator periods and total undulator length is important to increase FEL conversion efficiency and to reduce its size. The FEL consists of a magnetron-based microtron having an energy of ~5 MeV, a strong electromagnetic helical undulator having the period of ~25 mm, and a cylindrical waveguide-mode optical resonator. The total diameter of the microtron is approximately 50 cm and the macropulse current is more than 50 mA. The size of the system is expected to be 1x2 m^2. The condition for low-loss and high-gain oscillator of the table-top FEL has been studied by using a 2-D FEL code. Simple injection scheme of the electron beam to the undulator was optimized by calculating beam trajectories with a 3-D PIC code. The average THz power is calculated to be 1 W with the tunable wavelength range from 200 μm to 500 μm. The FEL is expected to be used for the real-time imaging of security inspection.

Keywords: table-top free-electron laser, terahertz radiation, security inspection, free-electron laser.

Ю. У. Джонг, Г. М. Казакевич, С. Х. Парк, К. Ли, Дж. Мун, К. Х. Янг, Дж. Ю. Ли, Дж. Сунву, К. Н. Ким, И. С. Ли, Ю. Х. Ча, Х. Ча, Д. Х. Ким, Б. Х. Ча

РАЗРАБОТКА КОМПАКТНОГО ТГЦ ЛАЗЕРА НА СВОБОДНЫХ ЭЛЕКТРОНАХ ДЛЯ СИСТЕМ БЕЗОПАСНОСТИ

Мы выполнили проект настольного ТГц лазера на свободных электронах (ЛСЭ). Основной момент при проектировании ЛСЭ – снижение потерь излучения в резонаторе ЛСЭ, кроме потерь, непосредственно связанных с выводом излучения. Кроме того, для увеличения эффективности ЛСЭ и уменьшения его размера важно сократить число периодов и общую длину ондулятора. ЛСЭ состоит из микротрона с энергией ~5 МэВ, работающего на магнетронах, мощного электромагнитного спирального ондулятора с периодом ~25 мм и цилиндрического волноводного оптического резонатора. Общий диаметр микротрона составляет примерно 50 см, а ток макроимпульса превышает 50 мА. Предполагается, что размер этой системы будет 1x2 м^2. Условия создания осциллятора с малыми потерями и высоким коэффициентом усиления были исследованы с использованием 2D моделирования ЛСЭ. Обычная схема инжекции пучка электронов в ондулятор была оптимизирована посредством 3D моделирования траекторий пучка программой PIC. По результатам вычислений, средняя ТГц мощность будет 1 Вт с диапазоном перестройки излучения от 200 μm до 500 μm. Ожидается, что этот ЛСЭ будет использоваться для визуализации в реальном времени при проверках с целью обеспечения безопасности.

Ключевые слова: настольный лазер на свободных электронах, терагерцевое излучение, проверка с целью обеспечения безопасности, лазер на свободных электронах.

ISSN 1818-7994. Вестник НГУ. Серия: Физика. 2010. Том 5, выпуск 4
Vestnik Novosibirsk State University. Series: Physics. 2010. Volume 5, issue 4

Introduction

Recently, there has been rapid increasing of developments on science and technology in terahertz (THz) range [1–5]. However, realization of powerful and compact source is one of the bottle lacks and important tasks of the THz science and technology. If we consider the serious THz absorption by atmosphere or materials and limited sensitivity of THz sensors, the required power for real-time THz imaging is still far from the power level of presently available small-scale THz sources. We estimated the required power of the THz source of real-time imaging for security inspection and it was 1-W level as shown in Fig. 1.

We have developed a compact THz free-electron laser (FEL) with a conventional microtron accelerator driver [6–7]. The FEL has been used for basic researches on THz applications [8–9]. Based on the experience, we are developing a table-top THz FEL which can be used for security inspection. The goal of our new project is to develop a table-top THz FEL for 1-W average power. In this paper we present on the design status of the FEL including compact microtron accelerator, undulator, and waveguide oscillator.

Design target of the table-top THz FEL

To realize a table-top THz FEL, we need a compact acclerator, a short beamline and an undulator, and all in a good and compact self-shielding. Target wavelength of the FEL for the security inspection is determined to be 200–500 μm by considering spectroscopic and transmittance property of the materials. The taget power of the THz radiation is 1 W. The system should be table-top or standng-rack style to be used for airports, ports or gates of facilities. To reduce radiation hazard and shielding load, we will use a rather low energy electron beam of ~5 MeV. To get the target wavelength range, the undulator period is set to be ~25 mm. And the magnetic field strength should be 3–7 kG to generate the target THz wavelength range. We will develope a short undulator having the period number of less

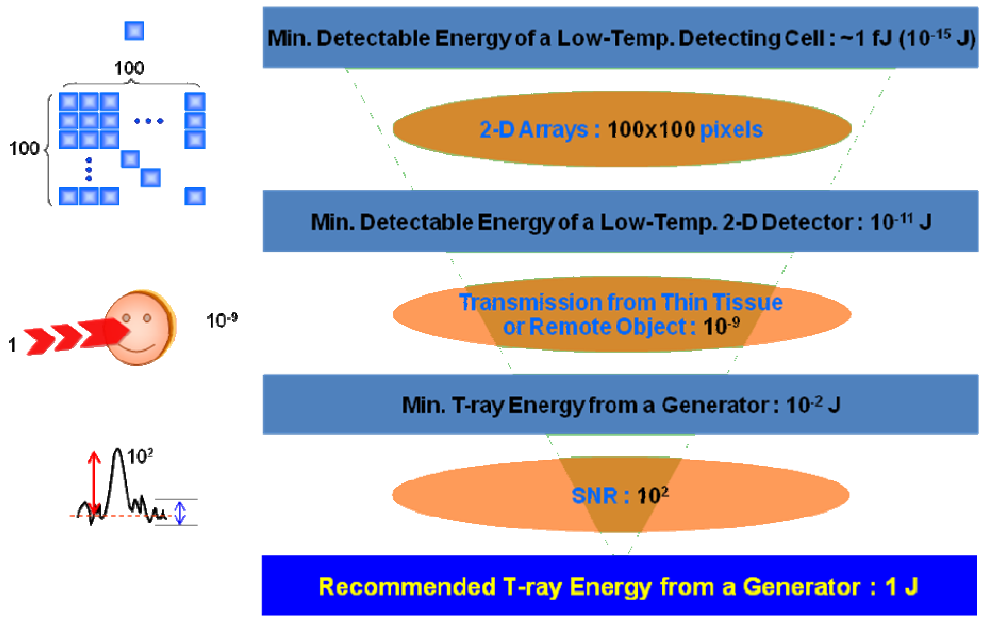

Fig. 1. Estimation of required THz power for real-time imaging for security inspection

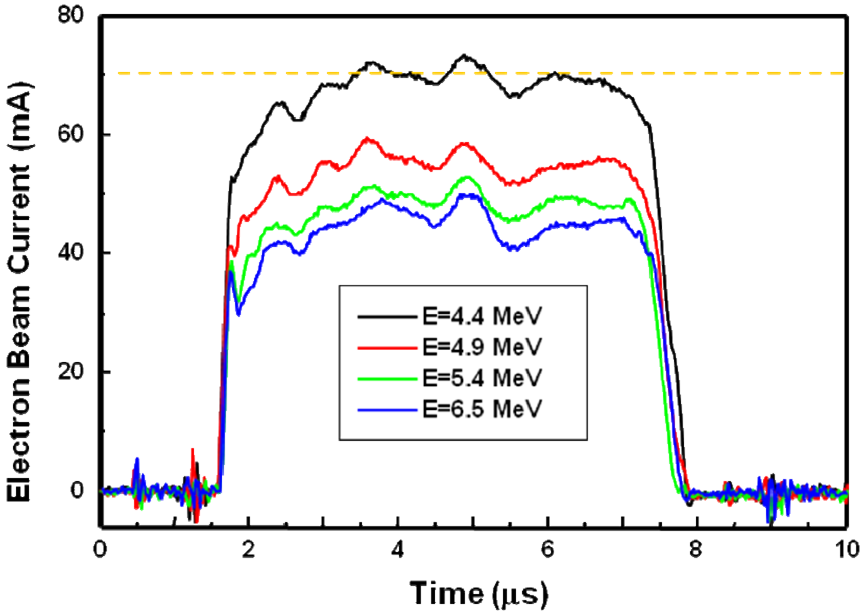

Fig. 2. Measured beam current of the microtron macropulse depending on the electron energies

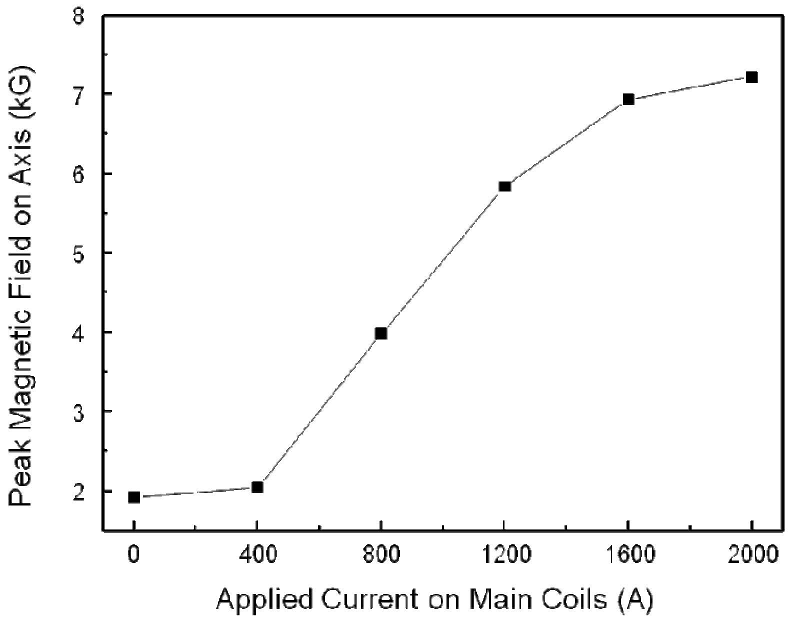

Fig. 3. Calculated magnetic field strength on the axis of the designed helical undulator

than 30. The main reason of the short undulator is to achieve a higher efficiency of the THz power from electron beam as well as compactness. The total length of the system might be approximately 2 m.

Compact microtron accelerator

We have studied and compared compact accelerators for the table-top FEL. The candidates of the accelerators were microtron or RF linear accelerators with thermionic gun or RF gun. If we consider the beam power, RF system, cost, shielding load, and size, a microtron driven by a magntron could be the best choice except low beam power. The microtron can generate quite good parameters of the electron beam. The energy spread and emittance could be less than 0.5% and 5 mm mrad in the energy range of 4-6 MeV, respectively. Such good quality of electron beam has an advantage of small radius of beam envelope in a strong undulator to increase the interaction with a strongly confined radiation mode in a small gap waveguide [1-2]. The required beam power of the accelerator is approximately 100 W. Based on our experience, we determined to develope a high-repetion rate microtron having a beam power of 100 W.

We have developed a conventional microtron accelerator which is driven by a radio-frequency (RF) source of a magnetron. The electron energy from the microtron is from 4.5 to 6.5 MeV depending on the turn number of electrons passing through the RF cavity and 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 beam power is more than 10 W for a 10 Hz macropulse repetition rate as shown in Fig. 2. If we upgrade the repetition rate up to 100 Hz, the beam power could be more than 100 W.

Undulator and waveguide-mode resonator

We have designed a hybrid electromagnetic (EM) helical undulator. The undulator has two superposed hybrid EM planar undulator deveolped for the KAERI THz FEL [1-2], which are placed with 90° rotation and phase shift of 1/4 period relative to each other. Blocks of permanent magnet (PM) are placed between adjacent iron poles to reduce the magnetic field saturation caused by coils. The dependence of the magnetic field strength on the current of the coils are shown in Fig. 3., which are calculated by a 3-D simulation code. We can get the field strength of 3-7 kG on the axis of the the undulator by changing the current from 600-1800 A. The value meets the requirement for the undulator.

We will use a cylindrical waveguide for the THz FEL oscillator to confine the THz mode. The diameter of the waveguide is just ~4 mm and we can increase significantly the interaction between electron and THz oscillation mode. The ratio of the mode cross-section between the free-space and waveguide mode is more than 10 times, which increases the small signal gain of the FEL with the same ratio.

The dispersion relation of the cylindrical waveguide is expressed as follows,

$$\frac{\omega^2}{c^2} = k^2 + \frac{x_{mn}^2}{R_{wg}^2},$$

where, R_{wg} is the radius of the waveguide and x_{mn} meets the condition of $J'_n(x_{mn})=0$ for TE-mode and $J_n(x_{mn})=0$ for TM-mode. By combining this relation and the FEL dispersion relation, which can be written as follows,

$$\frac{\omega}{c} = \beta_z\left(k + k_u\right),$$

we can get the mode-matiching condition of the waveguide-mode FEL

$$k = \left(\gamma_z^2 - 1\right)k_u \pm \gamma_z\sqrt{\left(\gamma_z^2 - 1\right)k_u^2 - \left(\frac{x_{mn}}{R_{wg}}\right)}.$$

In the case of R_{wg}=4 mm, the fundamental mode of TE_{11} can be excited in the FEL. The field distribution of the TE_{11} mode is shown in Fig. 4.

FEL operating wavelength with the waveguide of 2-mm radius could be calculated for the designed value of the helical undulator having the period of 25 mm and the field strength of 3-8 kG, which is shown in Fig. 5. We can find that the magnetic field strength of 4-7 kG meets the requirement of the FEL wavelength range of 200-500 m. The calculated loss of the TE_{11} for the wavelength range of 200–500 μm is 16-11% for 1-m-length and 4-mm-diameter waveguide as shown in Fig. 6.

Simulation results

We have calculated the small-signal gain of the waveguide-mode FEL. The length of the undulator should be determined by considering the gain and the loss of the waveguide mode. The length of the undulator was determined to be 700 mm and the length of the FEL oscillator can be less than 1 m. The calculated results of the gain depending on the undulator field

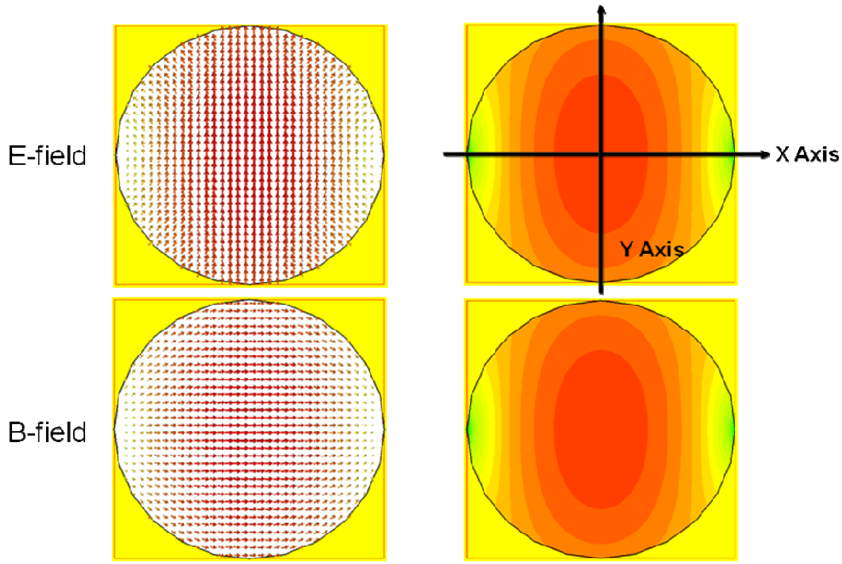

Fig. 4. Electric and magnetic field distribution of the TE_{11} mode in a cylindrical waveguide

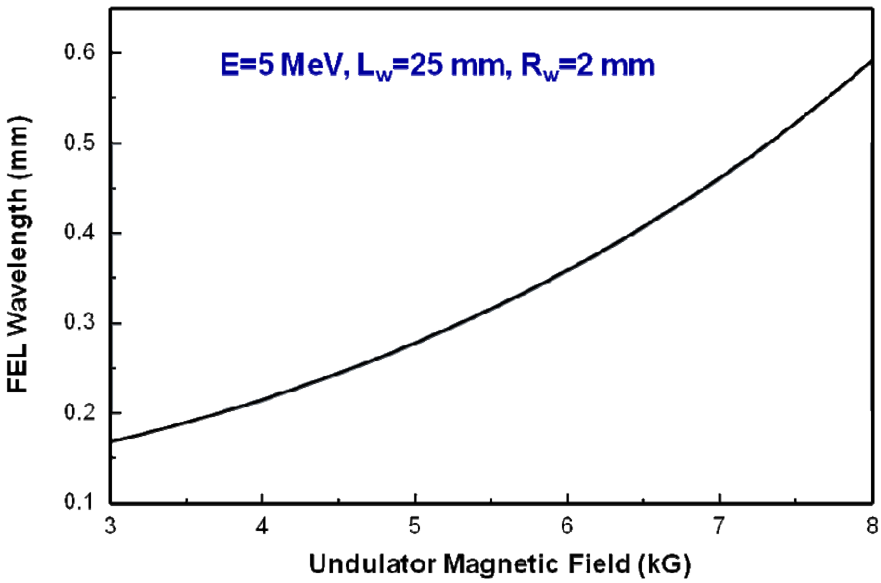

Fig. 5. FEL operating wavelength depending on the undulator magnetic field strength for the conditions of 5-MeV electron energy, 25-mm undulator period, and 2-mm radius of the cylindrical waveguide.

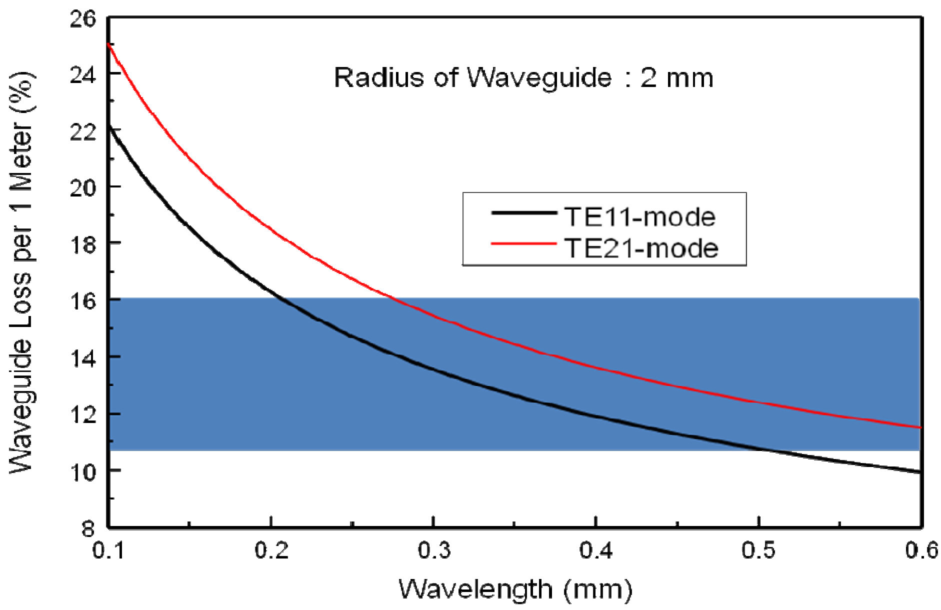

Fig. 6. Calculated loss of the TE_{11} mode of a cylindrical waveguide having 1-m-length and 4-mm diameter, which are compared with that of the TE_{21} mode for the THz range from 100 to 600 μm

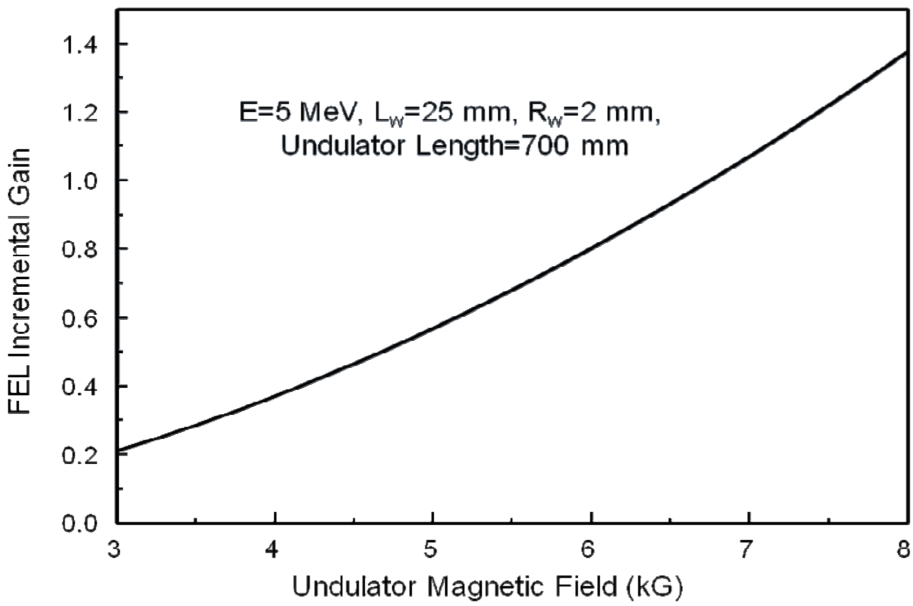

Fig. 7. Calculated small-signal gain of the waveguide-mode FEL depending on the undulator field strength from 3 to 8 kG

strength are shown in Fig. 7. We can find that the small-signal gain for the target wavelength range, that is 4-7 kG of the undultor field strength, is enough for the FEL oscillation.

Trajectories of the electron beam incident to the undulator have been calculated by a 3-D particle-in-cell (PIC) code. We found that the trajectories could be optimized for our small-gap waveguide-mode FEL. The calculated trajectories and beam envelope are shown in Fig. 8. We can see that the electron beam from the microtron could be transported through the

2-mm-radius waveguide in the helical undulator. Oscillation power evolution of the waveguide FEL has been calculated by a 2-D FEL simulation code for different output coupling ratios, which is shown in Fig. 9. We can find that the optimal output coupling ratio generates more than 30 kW of the THz FEL pulse power, which results in the average output power of 1 W for the repetition rate of 100 Hz.

As a conclusion of this paper, we can summarize the designed parameters of the table-top THz FEL in table 1. It should be noted that the results could be upgraded by the further researches for finding better ideas on the FEL.

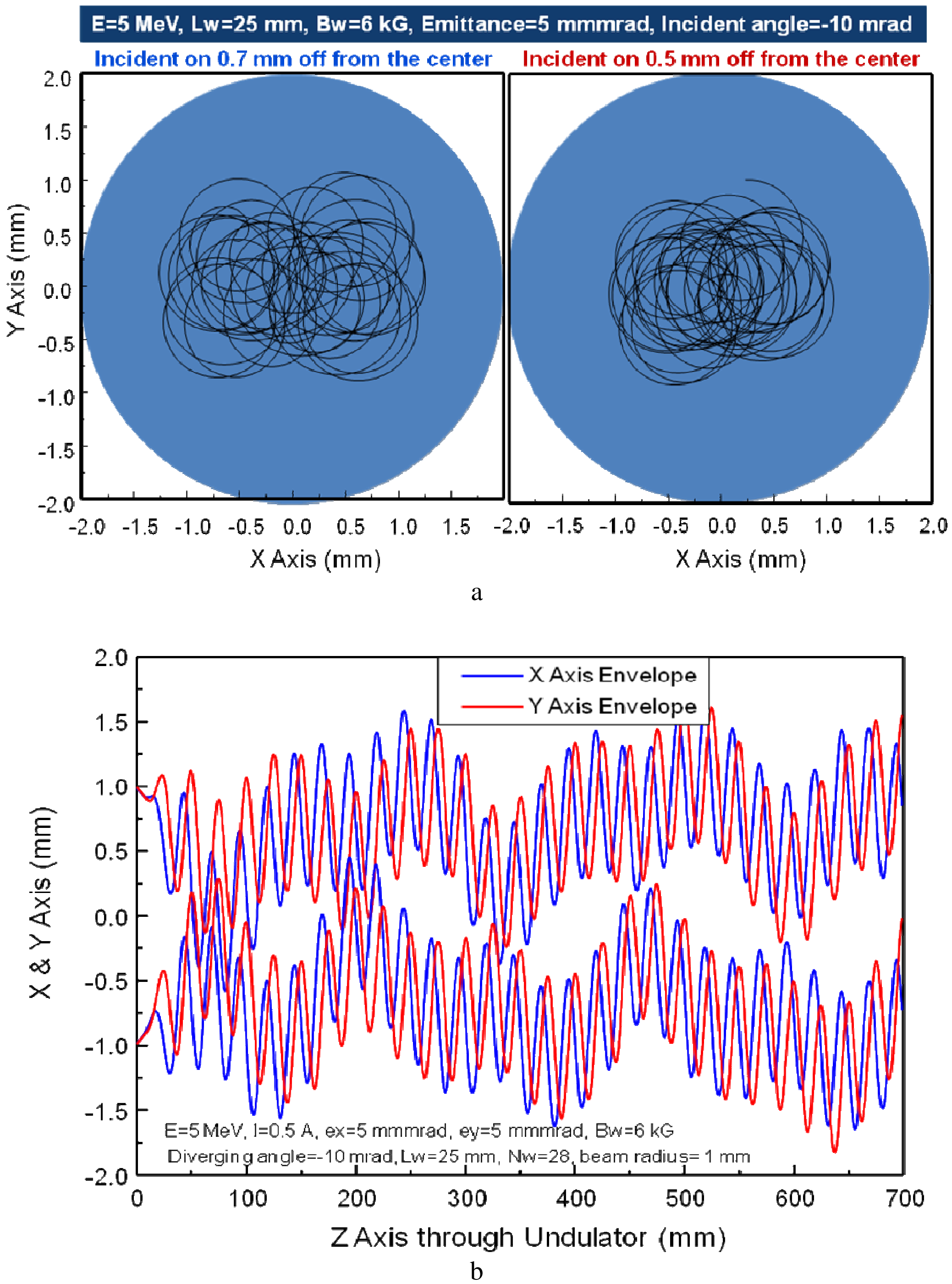

Fig. 8. Trajectories (a) and beam envelope (b) of the electrons incident to the undulator, which is calculated by a 3-D PIC code

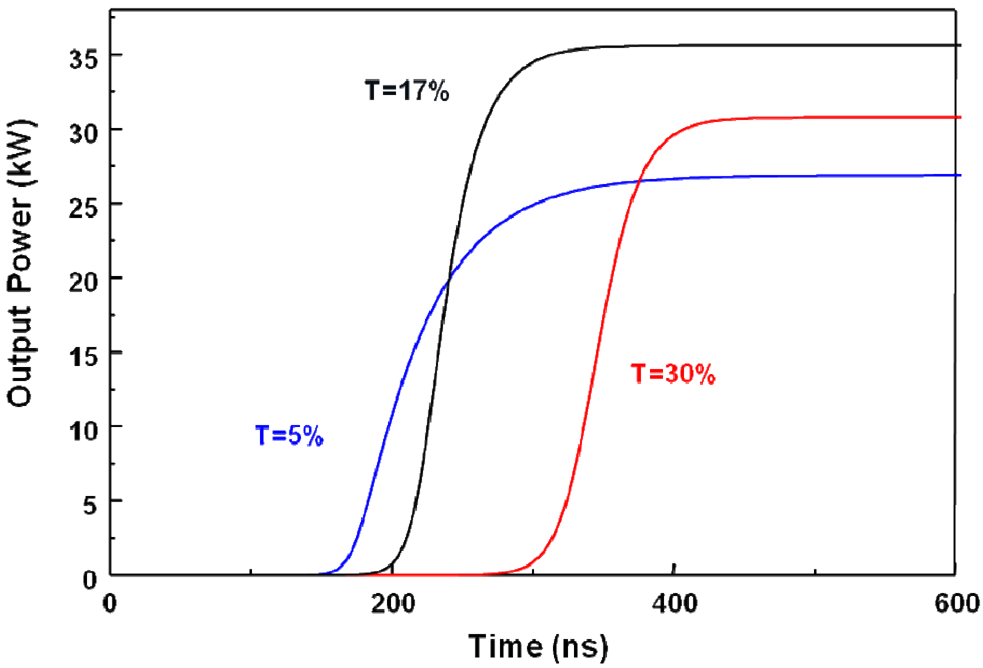

Fig. 9. Calculated oscillation power evolution of the waveguide FEL depending on output coupling ratio

Table 1. Designed parameters of the KAERI table-top THz FEL.

Electron Beam	
Energy (peak current)	5 MeV (0.5 A)
Emittance	< 5 mm mrad
Energy Spread	~0.4%
Undulator (Helical Type)	
Period (Number of Periods)	25 mm (28)
Peak Magnetic Induction (K-value)	4–7 kG (1–1.8)
Waveguide Mode & Radius	TE_{11}, 2 mm
THz Beam	
Radiation Wavelength (frequency)	200–500 μm (0.5–1.5 THz)
Average Power	~ 1 W
THz Micropulse	
- Pulse Duration	20~30 ps
- Power	20~30 kW
- Repetition Rate	2.8 GHz
THz Macropulse	
- Pulse Duration	4 μs
- Repetition Rate	100 Hz

References

1. *R. Kohler, A. Tredicucci, F. Beltram, H. E. Beere, E. H. Linfield, A. G. Davies, D. A. Ritchie, R. C. Iotti, and F. Rossi*, Nature. 417, 156. (2002).

2. *Q. Wu and X-C. Zhang*, Appl. Phys. Lett. 67, 3523. (1995).

3. *K. Kawase, Yuichi Ogawa, Yuuki Watanabe, and Hiroyuki Inoue*, Opt. Express 11, 2549. (2003).

4. *M. Abo-Bakr, J. Feikes, K. Holldack, and G. Wüstefeld,* Phys. Rev. Lett. 88, 254801. (2003).

5. *M. A. Dem'yanenko, D. G. Esaev, B. A. Knyazev, G. N. Kulipanov, and N. A. Vinokurov,* Appl. Phys. Lett. 92, 131116. (2008).

6. *Y. U. Jeong, B. C. Lee, S. K. Kim, S. O. Cho, B. H. Cha, J. Lee, G. M. Kazakevitch, P. D. Vobly, N. G. Gavrilov, V. V. Kubarev and G. N. Kulipanov*, Nucl. Instr. Meth. A 475, 47. (2001).

7. *Y. U. Jeong, G. M. Kazakevitch, B. C. Lee, S. K. Kim, S. O. Cho, N. G. Gavrilov, J. Lee*, Nucl. Instr. Meth. A 483, 195. (2002).

8. *G. N. Zhizhin, A. K. Nikitin, G. D. Bogomolov, V. V. Zavialov, Y. U. Jeong, B. C. Lee,*
S. H. Park, H. J. Cha, Optics and Spectroscopy, 100, 734. (2006).

9. *H. J. Cha, Y. U. Jeong, S. H. Park, B. C. Lee, S.-H. Park,* J. Kor. Phys. Soc. 49, 354. (2006).

10. *Y. U. Jeong, G. M. Kazakevitch, H. J. Cha, S. H. Park,* Nucl. Instr. Meth. A 575, 58. (2007).

22.09.2010