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Compact electron-accelerator system using laser-induced photoelectrons and DISKTRON electrostatic accelerator

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A new type of relativistic electron acceleration facility is being developed by the Laser Science Research Group at The Institute of Physical and Chemical Research. It utilizes laser-induced photoelectrons accelerated by a compact DISKTRON electrostatic accelerator, which makes it possible to generate a controllable bright short-pulsed electron beam up to the energy of 1 MeV with a low emittance ($<2\times10^{-5}$ mrad) and high current density ($\sim$500 A/cm^2) without any guiding field. The characteristics of the entire facility and some of the key components are described in detail. The experimental results which confirm the possibilities of increasing quantum efficiency of metal photocathodes by geometric alteration are reported. Observation of laser undulator effects in the visible wavelength was demonstrated in the facility. The coming use of the system includes a far-infrared/submillimeter free-electron laser using a microwiggler and generation of extreme ultraviolet radiation by the laser undulator.

I. INTRODUCTION

There are three main disadvantages of FELs compared to other types of lasers. They are (1) its high capital cost and size of an accelerator, (2) complexity of operation, and (3) need of rigorous radiation shielding. The initial cost of constructing a conventional accelerator such as a rf or induction linac, a storage ring, or a conventional electrostatic accelerator is enormous. As a result, one either has to share the accelerator facility with others having different objectives or construct the FEL as a user facility for a number of users.[1] In addition, most of the existing accelerator facilities require several personnel to operate and they are required to meet stringent safety regulations concerning x-ray/gamma-ray radiation.

We are developing a new type of facility which can produce a relatively low-energy electron beam ($\sim$1 MeV) with a low emittance ($<2\times10^{-5}$ m rad) and high current density at a focus ($\sim$500 A/cm^2) while circumventing most of the shortcomings mentioned above. It consists of an exceptionally compact electrostatic accelerator called DISKTRON[2] and a laser-induced metal photocathode employing the fourth-harmonic light of a Nd–YAG laser. It can be contained in a medium-sized laboratory room without extensive radiation shielding and it is even possible for one person to run an experiment. First we describe the DISKTRON electrostatic accelerator, the lasers used to produce photoelectrons, and the characteristics of the relativistic electron beam produced by the system. Quantitative arguments for the estimates of beam emittance and energy shift of the electron beam due to acceleration voltage drop are given. Second, we report a series of experiments that demonstrate a simple but effective way to increase the emission efficiency of a metal photocathode used in the electron gun by modifying the geometric structure of the surface. The scheme is to choose the direction of the light polarization and the shape of the target to maximize the probability that electrons can escape the surface of the metal. Finally, the applications and future prospects including a compact FIR/submillimeter FEL with a microwiggler and generation of visible/XUV light by a laser undulator[3–6] are presented.

II. DISKTRON ELECTROSTATIC ACCELERATOR AND LASER-INDUCED PHOTOCATHODE

Figure 1 shows the external view of the DISKTRON electrostatic accelerator. This system uses rotating disks instead of a pellet chain or a belt used in conventional electrostatic accelerators, which make it possible to keep the height of the unit low. One disk can generate approximately 250 kV, and 1 MV can be obtained by four disks driven by a common motor. The unit is filled with 10 atm SF_6 gas for insulation. This type of accelerator has a few advantages over the conventional electrostatic accelerator. The first one is low fixed and running cost, the second is easy maintenance, and the third is its compactness. We believe these are very important features to make FELs more accessible to a variety of users. Without any guiding field, the beam radius of electrons increases due to a space-charge effect. Let $r(z)$ be the radius of an electron beam at a distance z; $r(z)$ is known to be as follows:[7]

$$r(z)=\frac{a_0}{2}\left[1+\sqrt{1+2\kappa\left(\frac{z}{a_0}\right)^2}\right], \tag{1}$$

where a_0 is the size of the beam waist, $\kappa=(2I/\gamma^3 I_A)$, and I_A is the Alfven current. Equation (1) implies that it is difficult for a low-energy acceleration system to produce high electron current density without getting the beam diverged. Computer simulations of the electron-beam propagation in the accelerator tube have been performed using a simulation code that includes a space-charge effect and the effect of self-magnetic field of the beam. Among various types of extraction electrodes and voltages, one could find suitable conditions by which the low-energy and high current electron beam can be propagated through the accelerator tube. The

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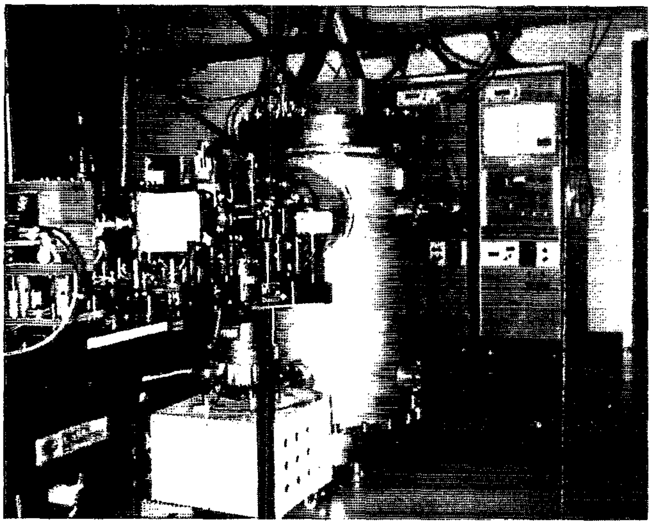

FIG. 1. External view of the DISKTRON electrostatic accelerator.

extraction voltage can be varied from 0 to 28 kV, and the acceleration voltage, in principle, can be chosen to be between a few hundreds of kV and 1 MV. However, the usable range of acceleration voltage is practically limited to around 500 kV and higher because the beam transport is inadequate bellow this value given the current design of the accelerator tube. We expect that this limitation can be eased with more optimization of the accelerator tube design, and work is under way.

We use laser-induced photoelectrons as the electron source. The fourth harmonic of a Nd–YAG laser is irradiated onto the surface of the metal photocathode. The material of the photocathode is aluminum, which can be exposed to the light for a long time in a modest vacuum ($\sim 10^{-5}$ Torr) without any degradation of quantum efficiency. The electron-pulse duration is almost a replica of that of the laser pulse. In our case a Q-switched Nd–YAG laser (DCR-11, Quanta-ray) produces pulses of 10 ns of time duration, and a mode-locked Nd–YAG laser (Antares 76-YAG, Coherent/RGA 60, Continuum) can generate 100 ps pulses. The laser power for the fundamental frequency of the mode-locked YAG is nearly 2 GW; however, it is reduced to 300 MW for the fourth harmonics. The experimental facility delineated in Fig. 2 shows the beam position monitor to measure the e-beam spot size at the focusing point for the laser undulator experiment as well as a graphite piece used to collect the total electrons in a pulse when the 45° bending magnet is off. The e-beam pattern was obtained by rad color film (Nittodenko), and the beam energy and current were 0.8 MeV and about 1 A, respectively. The diameter of the focused beam is found to be about 0.5 mm, which gives an electric current density of about 500 A/cm^2. The temporal characteristics of e beams were measured by a streak camera (PMA C2491-01/M2547, Hamamatsu) using Cherenkov light that is produced when the e beams hit the beam monitor made of a quartz plate. Figure 3(a) illustrates temporal structures of electron pulses depending on the power levels of the laser. The temporal resolution of the equipment is 10 ps. The residual pulse width without the laser on is determined by slit opening at the entrance of PMA and is measured to be 20 ps (that should be subtracted from the observed pulse width to obtain the actual width of the pulse). At the maximum laser power the pulse appears to be broadened, which tends to limit the maximum available peak current. We believe this is due to transportation characteristics of the acceleration tube rather than to additional thermal emission from heat depos-

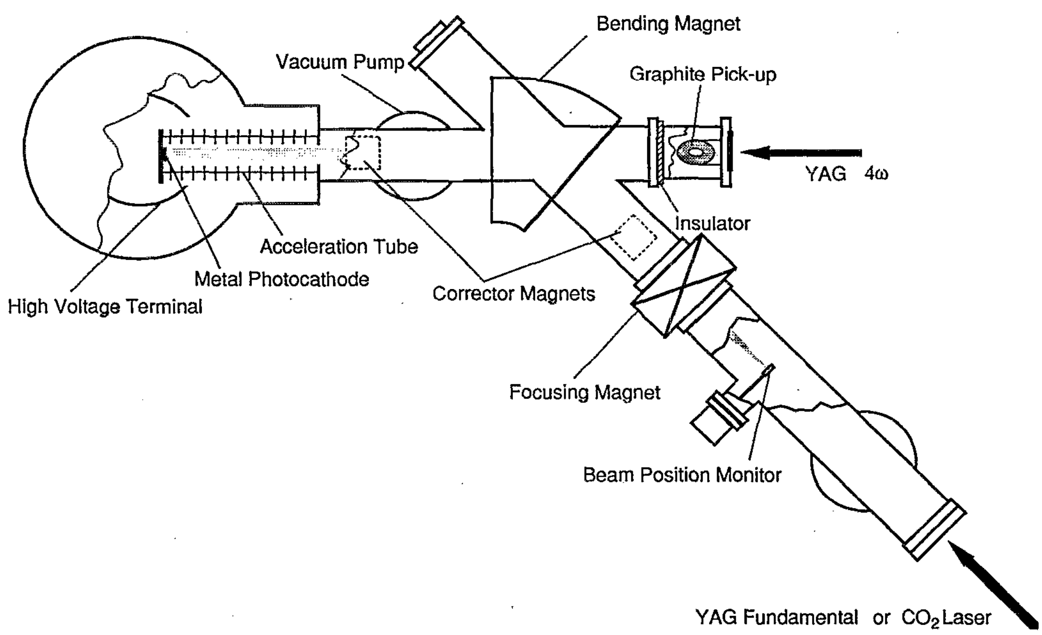

FIG. 2. Configuration of the experimental apparatus.

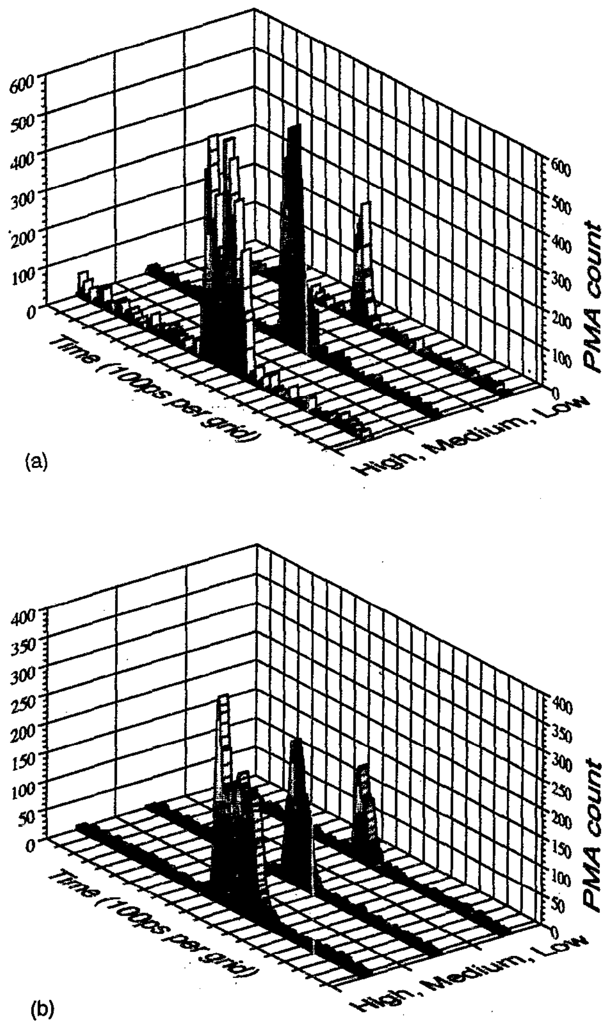

FIG. 3. (a) Temporal structures of *single-electron pulses* at low, medium, and maximum power. (b) Temporal structures of electron pulses *averaged over 25 pulses* at low, medium, and maximum power.

ited by the laser pulse since it should have a much slower response. Figure 3(b) shows the same type of measurement except that each type is averaged over 25 shots instead of a single shot. Relative jitters between a laser pulse and an e-beam pulse are found to be less than 10 ps (that was also confirmed in other measurement).

Emittance of an e-beam (ϵ) can be estimated using the following relations:

$$\epsilon \approx \theta d = Dd/f, \tag{2}$$

where θ is the divergence angle of the beam, f the focal length of the magnetic lens, d the diameter of the beam at the focus, and D the one at the entrance of the lens. Since $D<10$ mm, $f=300$ mm, and $d<0.5$ mm, we obtain then $\epsilon<1.7\times10^{-5}$ mrad. Subsequently, the energy shift of the e-beam due to an acceleration voltage drop can be calculated based on the following argument. In a pulsed operation the discharging current can deplete the charge in the high-voltage terminal so that the beam energy varies from the head of the pulse to the tail. Let ΔV be the difference in acceleration voltage caused by this type of event and V is the acceleration voltage, then the energy shift of the beam $(\Delta\gamma/\gamma)_{\rm drop}$ is expressed as follows:

$$\left(\frac{\Delta\gamma}{\gamma}\right)_{\rm drop} = \frac{\Delta V}{(V+V_0)} = \frac{I\tau}{C(V+V_0)}, \tag{3}$$

where V_0 is the voltage corresponding to the electron rest energy, i.e., $V_0 e = m_0 c^2$ (c being the speed of light), I the e-beam current, τ the pulse duration, and C the capacitance of the high-voltage terminal. Using the values $C=50$ pF, $V=0.85$ MV, $I=1$ A, and $t=100$ ps (mode-locked YAG), 10 ns (Q-switched YAG), then $(\Delta\gamma/\gamma)_{\rm drop}$ is calculated as 1.5×10^{-6} and 1.5×10^{-4}, respectively. Table I summarizes the pertinent parameters for our current system.

TABLE I. Characteristics of the electron beam obtained by the system.

Electron energy	0.7–1.0 MeV
Voltage stability	±2 kV
Beam current	>1 A (peak)
Pulse duration	10 ns (Q-switched YAG) 100 ps (mode-locked YAG)
Duty cycle	1 Hz (Q-switched YAG) 10 Hz (mode-locked YAG)
Current density at the focus	>500 A/cm^2
Emittance	$<2\times10^{-5}$ mrad
Energy shift due to acceleration voltage drop	$<2\times10^{-4}$ (Q-switched YAG) $<2\times10^{-6}$ (mode-locked YAG)
Charge-up current	25 μA for 1 MeV beam

III. EFFICIENCY ENHANCEMENT OF A METAL PHOTOCATHODE

In the last few years laser-induced photocathodes have become one of the most preferred methods to generate a bright short-pulsed electron beam.[8] However, no material that possesses both a high quantum efficiency and a high ruggedness has been found so far. Therefore one could either improve the properties of the efficient but more vulnerable materials or employ other means to enhance the efficiency of rugged ones. We have chosen to use the latter method for the improvement due to a rather moderate vacuum level in our experimental facility and our operational requirements such as high stability of operation and low maintenance.

There are several ways to improve photoelectron emission efficiency of a metal. One is to use surface plasma-wave excitation that can also be explained by Brewster angle reflection by modulated surfaces of complex refractive index.[9–11] This method appears to be very promising as long as the wavelength, incident angle of the laser light, and the pitch of the surface modulation are properly tuned. The second one is to employ a multiphoton process that requires a laser with very high power and short pulse.[12] The easiest and most general way to enhance the emission efficiency is to change the geometric shape of the target to fully utilize the surface emission, namely to choose the direction of the light polarization and the shape of the target to maximize the probability that electrons can escape the surface of the metal. It has been known that the quantum efficiency of the photoelectric effect depends on the relative relation between electric field and the plane of incidence.[13] In this experiment we

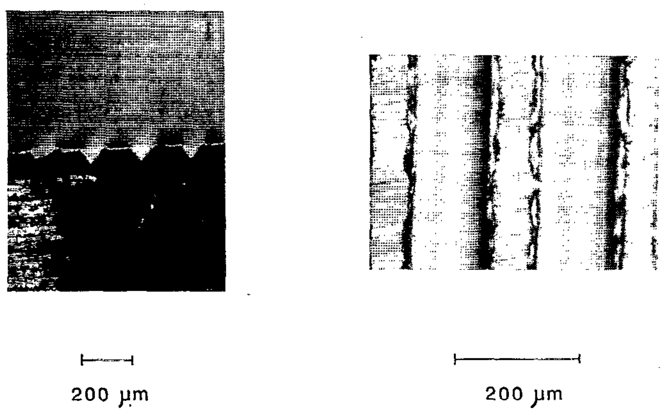

FIG. 4. Microscopical pictures of the grooved Al photocathode.

have shown a simple but effective way to increase the emission efficiency of a photocathode, especially at low power level of the input laser. In order to not degrade the beam emittance, a finely grooved target is used. The dimension of the grooves is much larger than the wavelength of the input laser to avoid unwanted interference. Figure 4 shows the microscopical picture of the edge and surface of the target. The angle of the slope with respect to horizontal direction is 55° and the area with grooves is 50% of the illuminated surface. This method can be used in a number of existing FEL photoinjectors just by replacing the target and adjusting the polarization of the laser.

A series of experiments was conducted in the configuration, a schematic of which is shown in Fig. 5. The fourth-harmonic light of a mode-locked Nd–YAG laser illuminates the target to produce an electron beam that is subsequently accelerated to the energy of 0.7 MeV. The e beam is wholly collected by a piece of graphite and the current is fed to a 50 Ω input. The laser power is initially measured by a power meter for calibration and is monitored by a p-i-n diode during the measurements. A half-wave plate is placed in front of the entrance-beam port to alter the direction of the polarization of the laser light. Signal pulses are fed into a boxcar averager/integrator (Stanford Research, SR250), and via a computer interface (SR245) the data go to a personal computer (Apple Computer, Macintosh Quadra700) in which

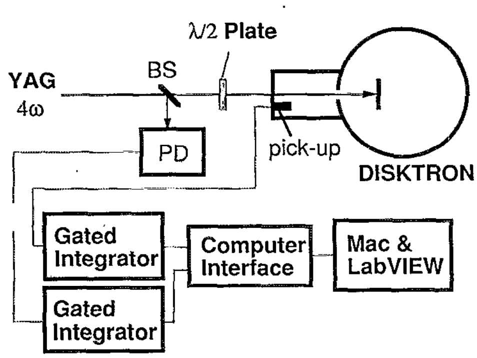

FIG. 5. Schematic of the experimental configuration for quantum efficiency enhancement scheme.

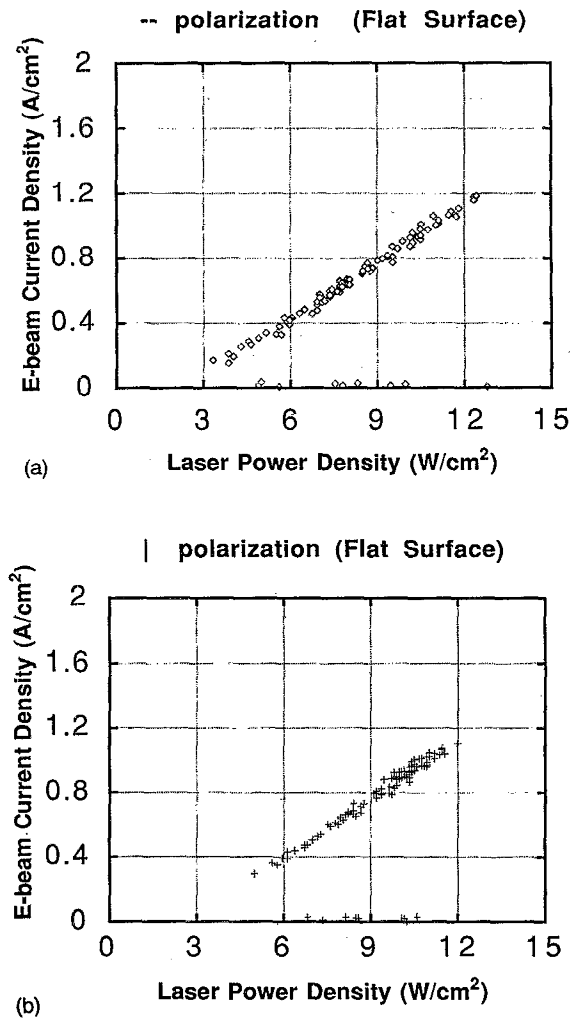

FIG. 6. Laser power density vs e-beam current for the light of (a) *horizontal* polarization and (b) *vertical* polarization using the *flat* target.

LabVIEW software[14] is run to analyze and graph out the data. The degree of polarization of the fourth harmonic of the Nd–YAG has been measured to be more than 90% and the use of the half-wave plate does not cause any difference in terms of the transmitted laser power on the target in two cases in which the direction of the light polarization is perpendicular each other. The grooves are lined vertically to the experimental plane so that the horizontally polarized light is regarded as P polarization.

Figures 6(a) and 6(b) show the relations between laser power density and produced e-beam current density for an aluminum target that has a flat surface. There is no clear difference between two cases with perpendicular polarization as is expected. Figure 7 is the result of the same kind of measurement after replacing the target with the one having a grooved surface. It is clearly shown that in the case of P-polarized light the yield is close to being twice as high as that by S-polarized light. Compared to the flat target at a given laser power, the former case gives slightly more than 3× higher quantum efficiency. S-polarized light with the grooved target appears to give higher value than the flat target, which may be due to increased roughness in a machined surface. Sporadic interruptions of the laser light to the target

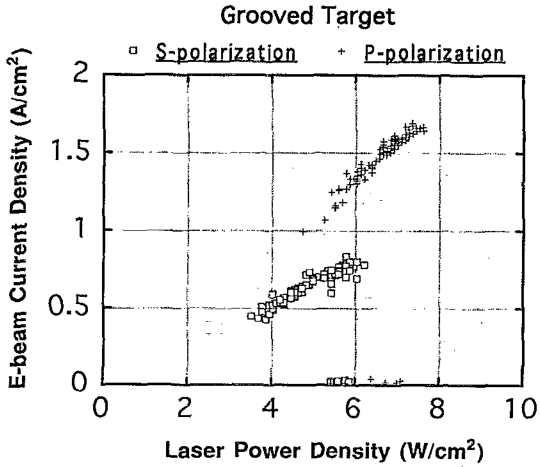

FIG. 7. Laser power density vs e-beam current for the light of P (+) and S polarization (□) using the *grooved* target.

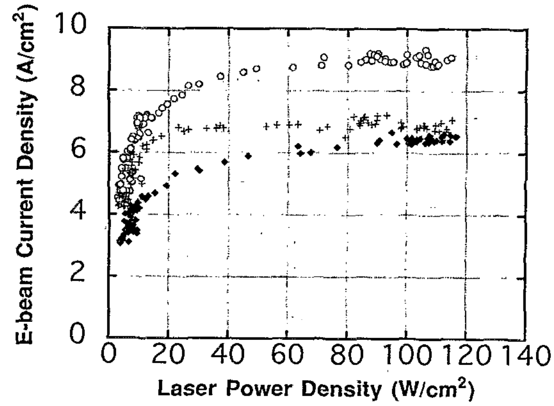

FIG. 8. Laser power density vs e-beam current with three different extraction voltages (V_{ex}): (♦) V_{ex}=7.0 kV, (○) V_{ex}=11.0 kV, and (+) V_{ex}=12.5 kV.

give the base line for ordinate, some points of which appear in figures, and careful calibration of instruments further assures that the measurements were done in equal condition in all cases. After taking it into account that only 50% of the surface has slopes, the real yield increase appears to be 3× or higher. Strictly speaking, the introduction of grooves would add a tangential component of the extraction electric field which could contribute the increase of e-beam emittance. However, the amount of tangential velocity acquired by the electrons within the distance of the order of 500 μm is fairly small compared to the final velocity and no noticeable degradation of emittance was observed after comparing the sizes of e-beam spots at the focus in two cases. As the laser power is increased further, the current density gets saturated. It appears that the maximum available value of the density is determined, not by the quantum efficiency of the cathode, but by transportation characteristics of the accelerator tube and extraction voltage. Figure 8 shows the saturation behaviors of the e beams with different extraction voltages. It looks that the e-beam current gets saturated at only less than one-third the available laser power, which implies further optimization of the tube design may increase the maximum current available now.

IV. APPLICATIONS AND FUTURE PROSPECTS

There are two main purposes of constructing this facility in the near future. One is a laser-undulator experiment both in the visible wavelength and in XUV; the other is realization of a compact FIR/submillimeter FEL using a microwiggler made of permanent magnets. There is an inherent energy spread caused by the acceleration mechanism of the electrons after the cathode, which is usually the most crucial factor in conventional FELs. This type of energy spread from the combination of an electrostatic accelerator and a laser-induced photocathode excluding space-charge effects is negligibly small since nonparallel components of the electron velocity are provided only by the energy that is on the order of the difference between the work function of the metal (~4.2 eV for Al) and the photon energy of the laser light (4.65 eV for λ=266 nm). In this experiment the e-beam energy spread caused by the space-charge effect is also small (~10^{-5}) due to the modest level of the current. We have so far observed visible emission from a laser undulator created by a TEA CO_2 laser. The details of the experiment are described elsewhere. We are currently working on the detection of XUV light by a laser undulator using the fundamental light from the Nd–YAG laser. As for the project of a compact FIR/submillimeter FEL, a new beam line is now completed to accommodate the wiggler. The favorable characteristics of an e beam from DISKTRON, such as low-energy spread and high beam brightness, in combination with the compactness of the accelerator, should make it possible to realize one of the smallest FELs available in the near future.

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