DEVELOPMENT OF PHOTOCACHODE DRIVE LASER SYSTEM FOR RF GUNS IN KU-FEL*

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Abstract

A photocathode drive laser system has been developed for RF guns in Institute of Advanced Energy, Kyoto University. Those RF guns require single-bunch and multi-bunch operation. Therefore, single-pulse and multi-pulse performances of the drive laser system have been examined for our laser system. As the result of test experiment, we have succeeded in generating UV laser pulses with micro-pulse energy of 205 μJ/micro-pulse in the single-pulse condition. On the other hand, in the multi-pulse condition, UV pulse lasers having flat macro-pulse shape with micro-pulse energy of 3.9 μJ and macro-pulse duration of 5 μs were successfully generated. Those values satisfy our target value required for the photocathode drive laser system and developed drive laser system will be used for electron beam generation.

INTRODUCTION

We have been developing an oscillator type mid-Infrared free electron laser (MIR-FEL) to contribute energy related sciences in Kyoto University [1]. The facility utilizes a 4.5-cell thermionic RF gun for its electron source. The gun can provide us high energy (~9 MeV) and multi-bunch electron beam with relatively long macro-pulse duration (~7 μs). However, the bunch charge is limited to less than 40 pC because of serious backbombardment effect [2]. Even with the limited bunch charge, we could provide MIR-FEL beam in the wavelength region from 5 to 20 μm. In addition to the MIR-FEL, development of THz-FEL has been started [3].

Two upgrade projects of MIR-FEL by modifying the thermionic RF gun have been carried out as well. One is a triode RF gun project [4] and the other is a photocathode project [5]. The triode RF gun uses a thermionic cathode and additional small cavity around the cathode. A numerical simulation predicted that the backbombardment effect could be solved by the proposed triode configuration [4]. The photocathode project is much simpler than the triode one. The photocathode RF gun driven by pico-second laser is completely free from the backbombardment effect and can produce electron beams with higher bunch charge and longer macro-pulse duration than the thermionic one. Initially we planned to install a modified BNL-type 1.6-cell RF gun to upgrade the MIR-FEL [6]. The gun cavity was manufactured in 2008. However, because of growing scientific interest in THz region, we changed our plan and decided to use the manufactured 1.6-cell gun as an electron source of compact single pass THz-FEL [3].

For the photocathode upgrade project of existing MIR-FEL device, we need to develop multi-pulse laser for oscillator FEL. On the other hand, single-pulse laser is enough for single pass THz-FEL. Our early work on the multi-pulse laser system was reported in the proceedings of FEL2012 [7]. At that time, we tried to develop a four-pass amplifier using a laser diode (LD) pumped amplifier module. In this scheme, however, we suffered from a self-oscillation of the amplifier module. Therefore we modified the amplifier configuration to have two double-pass amplifiers and installed nonlinear crystals for second harmonic generation and fourth harmonic generation. In this paper we will report the performance of our photocathode drive laser system.

PHOTOCATHODE DRIVE LASER SYSTEM

In this section, target values of our photocathode drive laser system and system configuration are described.

Target Values

There are so many choices for photocathode material and then the required performance of its drive laser strongly depends on the quantum efficiency (QE) of the photocathode. In this work, we assume usage of high QE photocathode (e.g. Cs-Te: QE > 1×10^{-2}) for the RF gun of multi-bunch operation and copper photocathode (QE ~ 1×10^{-4}) for the RF gun of single-bunch operation. Then we set the target bunch charge as 1 nC for both cases. Therefore the target micro-pulse energy of drive laser can be calculated as 0.47 μJ for the multi-bunch case and 47 μJ for the single-bunch case at the laser wavelength of 266 nm. The main parameters are shown in Table 1.

The maximum repetition rate of macro-pulse is given by the maximum repetition rate of RF power source used to drive the RF gun, which is 10 Hz in KU-FEL. The repetition rate of micro-pulse must be harmonics of 29.75 MHz which is a roundtrip frequency of optical cavity used for MIR-FEL. The number of micro-pulse determines the number of FEL amplification in the FEL optical cavity. A numerical simulation predicted that very high FEL gain (~ 300%) could be achieved with photocathode operation of 4.5-cell RF gun [5]. Therefore, not so large number of amplification is required but here we set the target number of micro-pulse to have more

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than 100 FEL amplifications in the cavity even it may be too much for MIR-FEL experiment.

Table 1: Target Values of Photocathode Drive Laser System

Bunch Charge		1 nC/micro-pulse
Laser Micro-pulse Energy @266 nm	Multi-bunch	0.47 μJ (QE > 0.01)
	Single bunch	47 μJ (QE ~ 1×10^{-4})
Macro-pulse Repetition Rate		≤ 10 Hz
Micro-pulse Repetition Rate		n × 29.75 MHz
Number of Micro-pulse (Multi-bunch case)		> n × 100

System Configuration

We used a mode-locked $Nd:YVO_4$ laser (GE-100-VAN-89.25MHz-CLX-Flexible AOM, Time-Bandwidth) as a laser oscillator. This laser's specifications are summarized in Table 2. The repetition frequency 89.25 MHz is one thirty second of the RF frequency of KU-FEL linac (2856 MHz) and third harmonics of roundtrip frequency of the FEL resonator cavity. The laser system was designed to synchronize the phase timing between the RF signal of KU-FEL and the repetition frequency of the drive laser by controlling the resonator length of the mode-locked laser. This oscillator has a built-in Acousto-optic modulator (AOM) for multi-pulse laser generation. The amplitude of pulse train generated from the oscillator can be arbitrary modulated by the AOM combined with an arbitrary waveform generator (AFG3251, Tektronix).

A beam alignment feedback system (Aligna4D, TEM) has been installed in the downstream of the AOM to stabilize both the laser beam position and angle whose drift can be caused by temperature drift of the AOM [7]. After that, two double-pass amplifier using a laser diode (LD) pumped amplifier (REA5006-2P1, CEO) which contains a Nd:YAG rod (ϕ5 mm × 12.6 cm) is employed. Finally, amplified laser pulses are injected to nonlinear crystals for second harmonic generation (SHG) and fourth harmonic generation (FHG). In this work, we used KTP crystal for SHG and KDP crystal for FHG. The photographs and schematic diagram of the multi-bunch laser system are shown in Fig. 1 and 2, respectively.

Table 2: Specification of Laser Oscillator

Wavelength	1064 nm
Repetition Rate of Micro-pulse	89.25 MHz (3 × 29.75 MHz)
Average output power	~600 mW
Pulse Duration	7.5 ps-FWHM
M^2 value	< 1.13 (x and y)

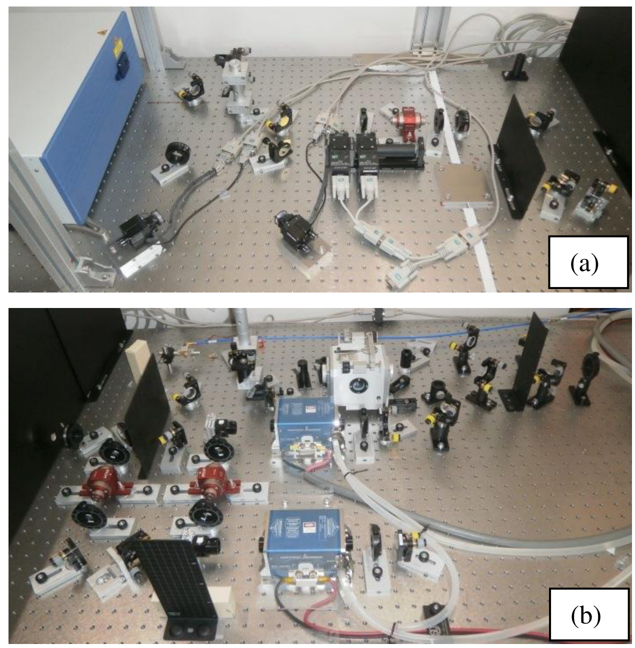

Figure 1: Photographs of the developed drive laser system. (a) Upstream side including the $Nd\text{-}YVO_4$ oscillator and the beam alignment feedback system. (b) Downstream side including the double-pass amplifiers and harmonic generation crystals.

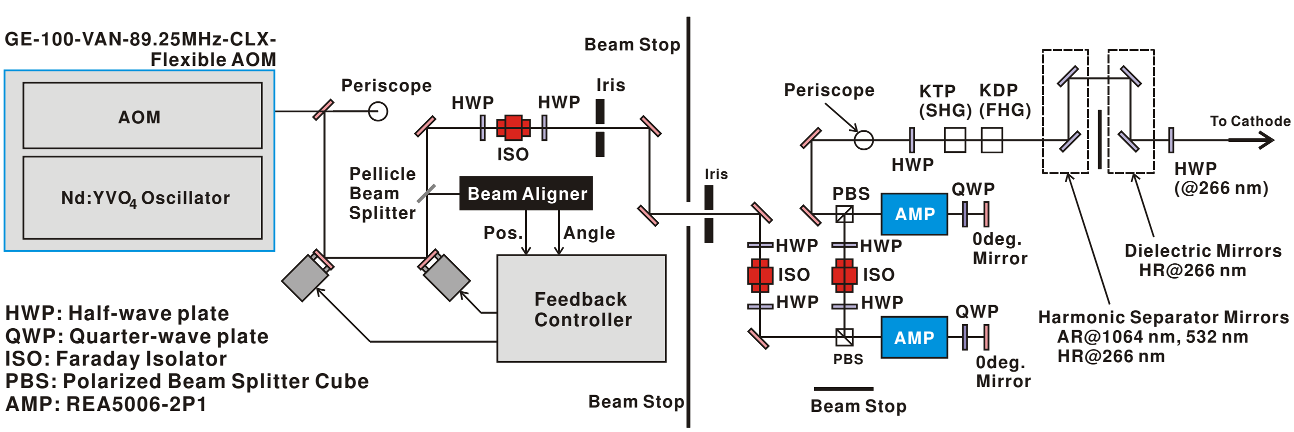

Figure 2: Configuration of photocathode drive laser system.

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PERFORMANCE TEST

The performances of developed laser system were tested under the single-pulse and multi-pulse conditions.

Single-pulse Condition

Single optical pulses were selected by AOM from 89.25-MHz pulse train generated by the mode-locked oscillator and sent to the two double-pass amplifiers. Figure 3 shows the observed laser pulse energy after two double-pass amplifiers as a function of LD current of 2nd amplifier with fixed LD current of 1st amplifier (80A). The laser pulse energy was measured by pyroelectric energy meter (PE10BB, Ophir). At the low LD current condition up to 65 A, the laser pulse energy exponentially increased on the LD current and its gain was 3 times/10 A. With the higher LD current than 65 A, the laser pulse energy shows saturation tendency, i.e. departure from exponential curve. The maximum fundamental pulse energy recorded was 2.5 mJ/micro-pulse. At the same time, the pulse energies after the second and the fourth harmonic generation crystals were measured. The results plotted with SHG and FHG conversion efficiencies are shown in Fig. 4.The maximum pulse energy after SHG and FHG were 686 and 205 μJ, respectively. The highest conversion efficiencies of SHG and FHG in this system were 38% at the fundamental pulse energy of 890 μJ and 38% at the second harmonic pulse energy of 338 μJ, respectively. The maximum overall conversion efficiency from IR to UV was around 14% at the fundamental pulse energy of 890 μJ. The achieved maximum pulse energy after FHG was much higher than our requirement, 47 μJ/micro-pulse. Here we conclude that the developed laser system has enough high performance for single bunch operation with copper photocathode whose quantum efficiency is around 1×10^{-4}.

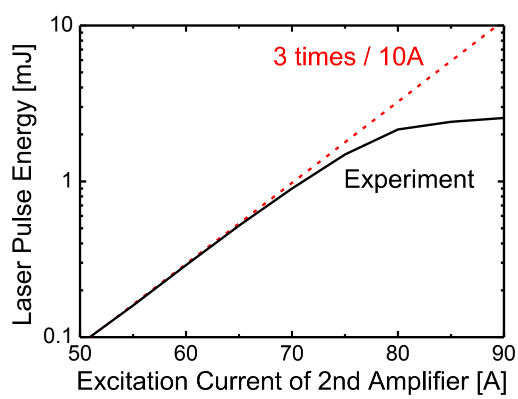

Figure 3: Laser pulse energy after two double-pass amplifiers as a function of LD excitation current of 2nd amplifier in case of single-pulse condition. The excitation current of LD in the 1st amplifier is fixed to 80 A.

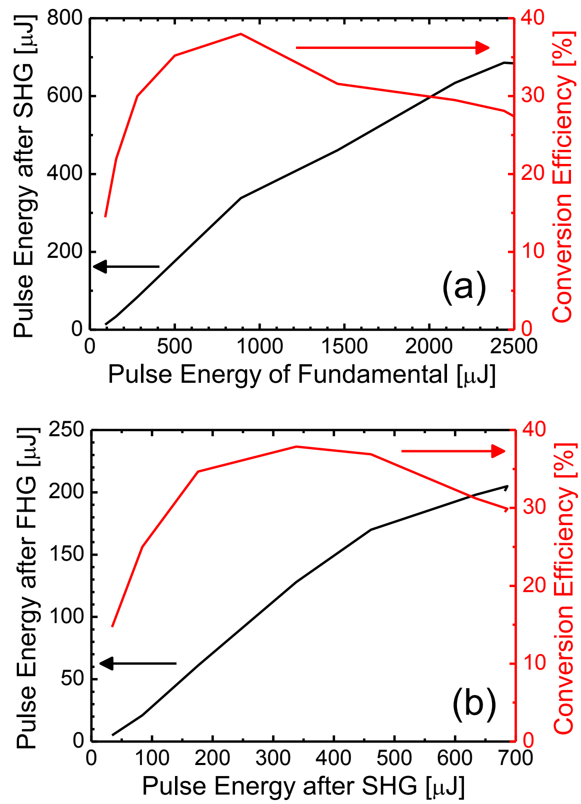

Figure 4: Laser pulse energy after SHG and FHG plotted with their conversion efficiencies as a function of incident laser pulse energy to the crystals. (a) Pulse energy after SHG and conversion efficiency of SHG. (b) Pulse energy after FHG and conversion efficiency of FHG.

Multi-pulse Condition

We tried to generate multi-pulse UV laser with a rectangular macro-pulse shape by modulating the built-in AOM. The macro-pulse structure and the macro-pulse energy was measured by an ultrafast photodetector (UPD-300-UD, ALPHALAS) and the pyroelectric energy meter (PE10BB, Ophir), respectively. A result is shown in Fig. 5. The pulse shape of UV laser is plotted with the control voltage of the AOM. As shown in Fig. 5 (a), almost flat macro-pulse could be generated by providing optimized control voltage to the AOM. The macro-pulse energy and the macro-pulse duration were 1.75 mJ and 5 μs, respectively. Then the micro-pulse energy was calculated as 3.9 μJ from those values and micro-pulse repetition rate of 89.25 MHz. The micro-pulse energy and macro-pulse duration satisfy our target values which listed in Table 1. With this condition, we can generate electron beam with bunch charge of 1 nC from a photocathode having QE of 1.2×10^{-3}. In order to show the importance of optimization of the AOM modulation pattern, a result of UV pulse shape measurement under the condition of rectangular AOM modulation pulse is shown in Fig. 5 (b). Since the micro-pulse energy of IR laser pulses in the second amplifier module were very high, the optical pumping power given by the LD in amplifier module was insufficient to maintain laser gain

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during the macro-pulse. Therefore the micro-pulse energy after second amplifier rapidly decreased during the macro-pulse. Therefore we need to optimize the modulation of AOM for generating UV laser pulse train having the rectangular macro-pulse structure.

In the optimized condition, the overall conversion efficiency from IR to UV can be estimated as 3% from the achieved UV micro-pulse energy (3.9 μJ/micro-pulse) and result of conversion efficiency measurement in single pulse condition shown in Fig. 4. By adding focusing optics before the nonlinear crystals and reducing the laser beam size on the crystals, the conversion efficiency in the multi-bunch condition can be increased. If we cannot use high QE photocathode, we need to optimize the laser beam size on the nonlinear crystals to have higher UV micro-pulse energy in the multi-pulse condition.

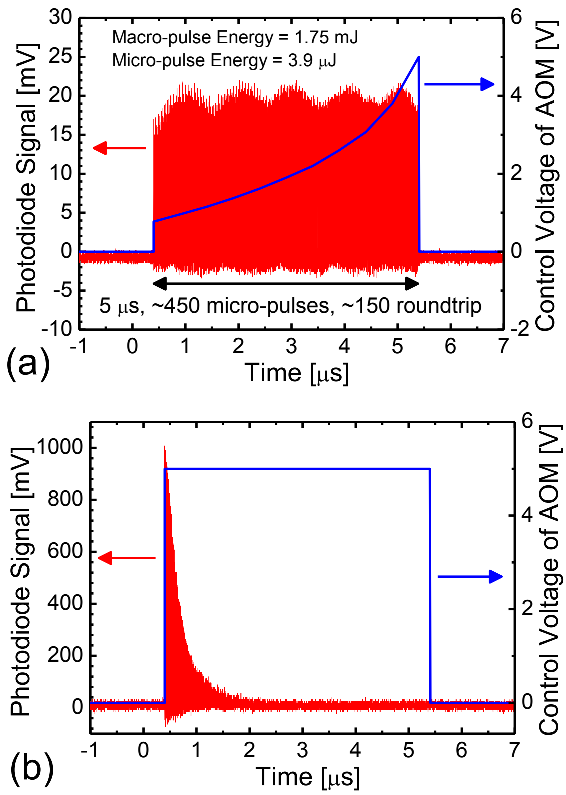

Figure 5: Measured UV pulse train with optimized amplitude modulation of AOM (a) and rectangular modulation of AOM (b). The periodic oscillation of peak value seen in figure (a) was caused by insufficient sampling speed of oscilloscope.

CONCLUSION

A photocathode drive laser system has been developed for photocathode RF guns in Institute of Advanced Energy, Kyoto University. The developed system consists of an $Nd:YVO_4$ mode-locked oscillator with a built-in AOM, beam position stabilization system, two double-pass amplifiers and nonlinear crystals for harmonic generation. Performance tests have been conducted with single-pulse and multi-pulse conditions. In case of the single-pulse condition, the maximum IR micro-pulse energy and maximum UV micro-pulse energy were 2.5 mJ and 205 μJ, respectively. In the experiment, the maximum overall conversion efficiency from IR to UV was around 14%. In case of multi-pulse condition, we have succeeded in generating UV laser pulses having flat macro-pulse shape with 3.9-μJ micro-pulse energy and 5-μs macro-pulse duration by applying optimum control voltage to the built-in AOM. Those values satisfies our requirements, i.e. generation of electron beams having 1-nC charge per bunch, and the developed laser will be used as the photocathode drive laser of RF guns in Institute of Advanced Energy, Kyoto University.

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