RE-COMMISSIONING OF THE FAR-INFRARED FREE ELECTRON LASER FOR STABLE AND HIGH POWER OPERATION AFTER THE RENEWAL OF THE L-BAND LINAC AT ISIR, OSAKA UNIVERSITY

R. Kato, S. Kashiwagi,T. Igo, Y. Morio, G. Isoyama[#]
Institute of Scientific and Industrial Research, Osaka University, Osaka, Japan

Abstract

The far-infrared FEL at the Institute of Scientific and Industrial Research (ISIR), Osaka University, which was operated in the wavelength region from 32 to 150 μm and was suspended since 1998, is being commissioned for stable and high power operation. The FEL is based on the L-band electron linac constructed in 1978, but it was largely remodelled for higher stability and reproducibility of operation as well as for long pulse operation for FEL. The long pulse mode has been successfully commissioned using a feed forward control system, which can stabilize the amplitude and the phase of the 1.3 GHz RF power in the macropulse within 0.5 % in amplitude and 0.3° in phase. The FEL system is the same as before except for the strong focusing wiggler based on the edge-focussing scheme, which was recently introduced. The FEL experiment is all set up and we are waiting for the next machine time and lasing.

INTRODUCTION

We have been developing a far-infrared FEL since late 1980s based on the 40 MeV, L-band electron linac at the Institute of Scientific and Industrial Research (ISIR), Osaka University. The first lasing was obtained at 32~40 μm in 1994 [1] and since then we progressively modified the FEL system and continued experiment in between to expand the wavelength region toward the longer wavelength side beyond 100 μm. We finally obtained lasing at 150 μm in 1998 [2], which was, at that time, the longest wavelength obtained with FELs based on RF linacs. We could not obtain power saturation because the macropulse duration is 2 μs, though the RF pulse is 4 μs long, due to a long filling time of the acceleration tube of the L-band linac and the number of amplification times is limited to 50 only. The linac was constructed approximately 30 years ago and it was not suitable for stable and high power operation of FEL, so that we suspended the development of the FEL.

In 2002, we had an opportunity to remodel the linac largely for higher stability and reproducibility of operation. We also added a new operation mode for FEL in which the macropulse duration can be extended to 8 μs. I took time to remodel the linac and commission it, but finally the operation mode for FEL is being commissioned and we are resuming the FEL again after the long suspension. We will report the progress and the current status of the re-commissioning of the FEL.

RENEWED LINAC

The linac is comprised of a thermionic electron gun, a three-stage sub-harmonic buncher system with two 108 MHz RF cavities and a 216 MHz cavity, a pre-buncher, a buncher, and a 3 m long accelerating tube. The last three components are excited by a single klystron of the 1.3 GHz frequency, the maximum peak output power of 30 MW, the pulse duration of up to 8 μs, and the repetition frequency of 60 Hz. The main parameters of the linac are listed in Table 1. A klystron modulator, which provides high voltage pulses to the klystron, has two operation modes; one is the normal mode with the pulse duration of 4 μs and the repetition rate of 60 pps and the other is the long-pulse mode with 8 μs and 30 pps. The operation modes can be changed manually but easily in a short time.

The maximum output power of the klystron is limited to 25 MW in the long pulse mode, so that the maximum beam energy in the multi-bunch mode used for FEL is slightly lower than 40 MeV.

Stability and reproducibility of linac operation are essential for advanced studies with the linac, including FEL and all the possible measures have been taken in the remodelling to reduce fast fluctuations and long-term drifts. Most influential power supply for the stability is the klystron modulator and it is designed and fabricated to reduce pulse-to-pulse fluctuations less than 0.1 %. Voltage ripples on the flat top of the square pulse applied to the klystron should be less than 0.1 % in order to make the amplitude and the phase of the output power from the

Table 1: Main Parameters of the L-Band Linac

Acceleration frequency	1.3 GHz
Sub-harmonic buncher	108 MHz×2, 216MHz×1 λ/4 coaxial resonators
Accelerating structures	Prebuncher×1, Buncher×1, Accelerating tube×1 Travelling wave, 2π/3 mode
Electron gun	Thermionic cathode (EIMAC YU-156), DC 100 kV
Operation modes, peak currents or maximum charge, and pulse durations	Transient: 1.9 A, 8 ns Single bunch: 91 nC, 20 ps Steady: 1.9 A, 4 μs Multi-bunch: 1.9 A, 8 μs
Repetition rate	≤ 60 pps
Klystron	30 MW×1
Total length	10.5 m

[#] isoyama@sanken.osaka-u.ac.jp

klystron constant over the macropulse duration. Figure 1 shows a voltage pulse applied to the klystron with the klystron modulator in the normal mode and a histogram showing the intensity fluctuation in longer than two hours. The undulation of the flat top in the normal mode is measured to be 0.21 % (peak to peak) over the time period of 3.5 μs, which is twice as large as the design goal, but it is much less in the latter third, while the fluctuation of the peak voltage is 0.06 % (two standard deviations) in two hours, which meets the specifications.

Most popular operation modes of the linac are the transient mode used for the pulse radiolysis study in the nanosecond region and the single bunch mode for pulse radiolysis in the sub-picosecond region as well as SASE experiment in the far-infrared region, and hence they are first commissioned to resume the joint-use of the linac.

MULTI-BUNCH MODE FOR FEL

In FEL experiments, the linac is operated in the multi-bunch mode, in which the second 108 MHz and the 216 MHz cavities of the sub-harmonic buncher system are switched on and the 1.3 GHz RF power of 8 μs duration is provided to the accelerating structures so that the multi-bunch beam with time intervals of 9.25 ns between bunches, which is the inverse of 108 MHz is accelerated. In order to make the peak of the energy spectrum of the multi-bunch beam sharp and to make intervals between bunches precisely equal, the amplitude and the phase of the RF power must be constant over the macropulse period. It is said that the amplitude and the phase of the output power from a klystron do not vary in a pulse provided that the flat top of the high voltage pulse applied to the klystron is flat and constant. As the first step for commissioning of the multi-bunch mode for FEL, we began with the steady mode with the macropluse duration of 4 μs, in which the sub-harmonic buncher system is not turned on. Although the condition is met in our case, we could not make the peak of the energy spectrum for the steady mode sharp. We, therefore, measured the amplitude and the phase of the RF pulse from the klystron in the normal mode and found that the amplitude varied by 3.1 % for the most flat part of 2.9 μs and the phase also varied by ~12 degrees in 3.4 μs, both of which are much larger than our expectation of < 1 % in amplitude and < 1 degree in phase.

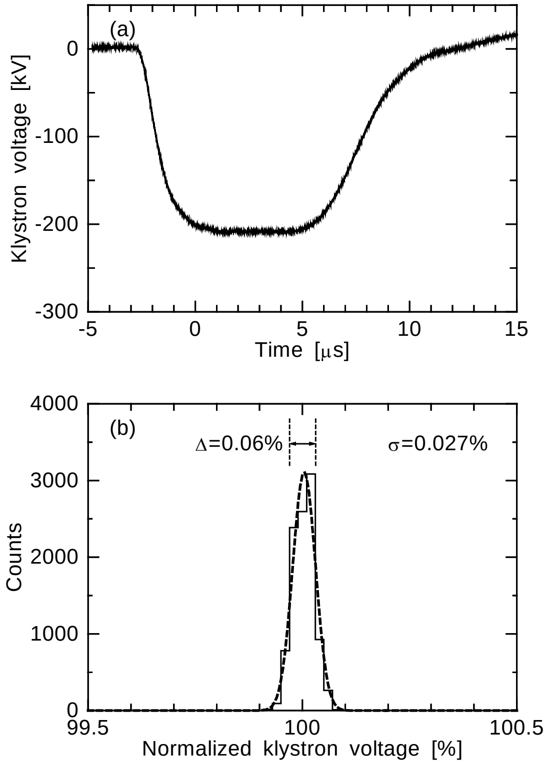

Fig. 1. High voltage pulse provided to the klystron in the normal mode and a histogram showing the peak intensity fluctuation.

Since reproducibility and stability of the high-voltage pulse from the klystron modulator are high and accordingly those of the amplitude and the phase variations of the RF power from the klystron are also high, we have adopted the feed-forward method to compensate for these variations. Figure 2 shows a block diagram of the compensation system for the amplitude and the phase of the 1.3 GHz RF power provided from the klystron to the accelerating structures of the linac. We, for the moment, adopt an analogue phase shifter with PIN diodes for phase control and an I-Q modulator for amplitude control. A part of the RF power is taken at a directional coupler on a waveguide from the klystron to the linac. The amplitude of the RF power is measured with a diode detector and the phase is measured with a phase detector, both of which have sufficiently fast response times, and the output signals are analysed with a digital oscilloscope. A personal computer calculates waveforms to be applied to the phase shifter and the variable attenuator so that both amplitude and phase variations becomes constant and flat over the RF pulse. Among the various components in the RF line, the phase shifter and the AB-class transistor amplifier, which is denoted by 300W amplifier in Fig. 2, have relatively long response times. In order to compensate for the slow response time, we use overdrive technique and the equation

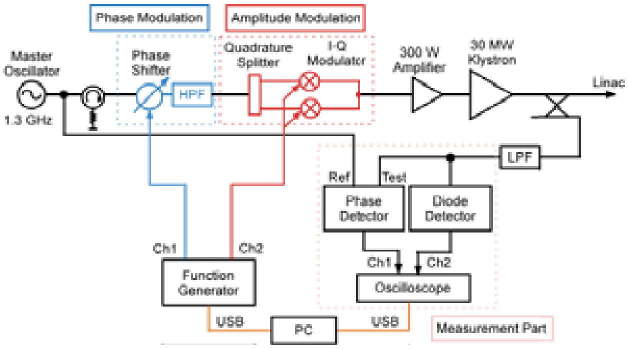

Fig. 2. Block diagram of the compensation system for the amplitude and the phase of the 1.3 GHz RF power from the klystron.

$$V_{in}(t-\Delta t) = V_c(t) + \tau \frac{dV_c(t)}{dt} \qquad (1)$$

is used to calculate the waveform generated with the function generator and applied to the control devices, where V_c is the control voltage for the ideally fast responding system, τ the response time of the system, Δt is the delay time in the control and measurement system, and V_{in} the actual control voltage. The response time and the delay time are measured with the actual system and they are τ = 50 ns and Δt = 540 ns for the amplitude control and τ = 780 ns and Δt = 640 ns for the phase control. Figure 3 shows the amplitude and the phase variations of the 1.3 GHz RF power in the long pulse mode before and after the compensation. The amplitude varies by 14.8 % in 7.4 μs and the phase by 13.5° before the compensation and they are reduced to 0.5 % and 0.3°, respectively, after compensation iteratively made several times.

Another problem we ran up against in the commissioning of the multi-bunch mode is that a correct energy spectrum could not be measured due to a digital current meter used for a Faraday cup in the momentum analyser, which is newly introduced in the upgrade of the linac in place of an old analog current meter, because it does not measure a correct current for an electron beam longer than a microsecond. It took time to find the current meter responsible for it. The long pulse electron beam is accelerated with the corrected RF power and energy spectra are measured with another momentum analyser with a fluorescent plate and a CCD camera. Figure 4 shows energy spectra of electron beams with several different time durations accelerated in the long pulse mode without the SHB system, which we call the steady mode. The filling time of the accelerating tube is approximately 2 μs and energy spectra for the electron beams with pulse durations shorter than it have broader peaks due to the transient effect, while the sharp peaks grow up on the lower energy side in the energy spectra of electron beams longer than the filling time or 2 μs. The electron beam is easily conditioned in the multi-bunch mode with the SHB system being on and thus the multi-bunch mode for FEL is successfully commissioned.

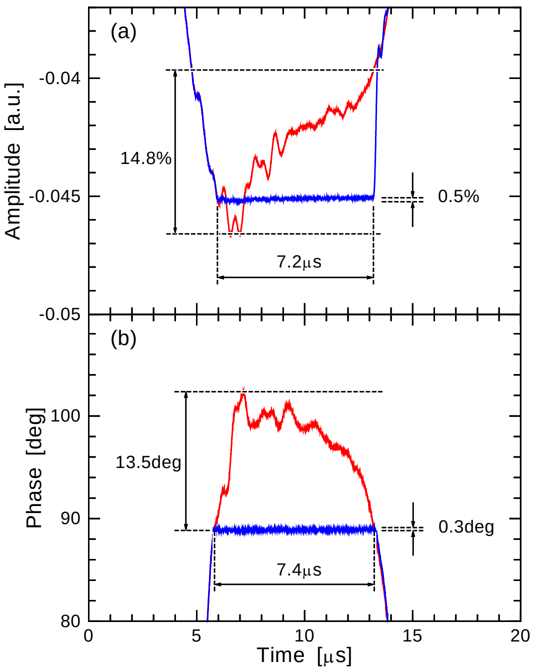

Fig.3. Amplitude and the phase of the 1.3 GHz RF power for the linac before and after the compensation. The panel (a) shows the amplitude and (b) the phase, while the red and the blue lines before and after compensation, respectively.

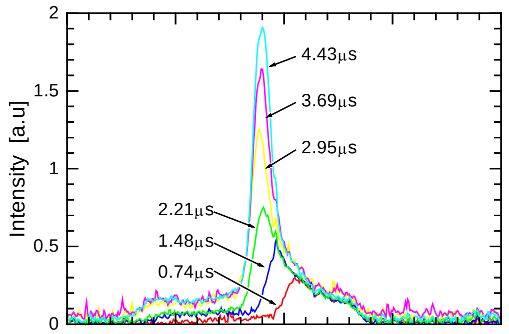

Fig. 4. Energy spectra of electron beams with several time durations in the long pulse mode without the SHB system.

FEL SYSTEM

The infrared FEL system, main parameters of which are listed in Table 2, is the same before the suspension except for the wiggler. The multi-bunch beam accelerated with the L-band linac is transported through the beam transport line consisting of two bending magnets and several quadrupole magnets to the wiggler. We used a conventional planar wiggler, but the magnet arrays were replaced with new ones that can not only wiggle the electron beam but also focus it both horizontally and vertically [3.] Figure 5 shows the magnetic field and the field gradient in the vertical direction measured along the beam axis of the strong focus wiggler at the magnet gap of 3 cm. The period length is 6 cm and the number of periods is 32, which are the same as before. The maximum peak magnetic field is 0.39 T at the minimum gap of 3 cm, which is slightly higher than before because permanent magnet materials advanced in the meanwhile. The FODO structure is adopted for the double focusing so that the electron beam of any energy accelerated with the linac can be focused even at larger wiggler gaps. The wiggler consists of four FODO cells and the cell length is 0.48 m. The focusing and the defocusing units are single wiggler periods with edge angles ±5° and the drift space is four normal wiggler periods. The maximum field gradients are ±3.2 T/m at the gap of 3 cm. The new wiggler was developed and installed for SASE experiments in the far-infrared region being conducted

Table 2: Main Parameters of the Infrared FEL

Wiggler	
Permanent magnet	Ne-Fe-B
Period length	6 cm
Number of periods	32
Magnet gap	12 – 3 cm
Peak magnetic field	0.39 T
K_{rms}-value	0.013 – 1.556
Total length	10.5 m
Focusing type	Strong focus with the edge-focusing scheme
Maximum field gradient	3.2 T
Length of FODO cell	0.48 m
Number of FODO cells	4
Optical resonator	
Type	Concentric resonator with spherical mirrors
Length	5.531 m
Mirrors	
Type	Spherical copper mirrors coated with gold
Curvature radii	3.358 m (upstream), 2.877 m (downstream)
Diameter	8 cm
Rayleigh range	1 m
Output coupling	3ϕ hole at the center of the upstream mirror

with the wiggler, but the FEL gain will be enhanced with it.

The optical resonator is a concentric resonator consisting of two spherical mirrors with different curvature radii. It is 5.531 m long and four optical pulses bounce back and forth in the cavity. The two mirrors are installed asymmetrically to the wiggler due to limitations by the magnets and other components in the FEL beam line and the curvature radii are chosen so that the waist of the stored light is located at the center of the wiggler. The FEL light is taken out through a hole at the center of the upstream mirrors and it is led with mirrors to the measurement room through the evacuated optical transport line, where the low vacuum in the optical transport line is separated with a synthetic diamond window from the high vacuum in the FEL beam line. The FEL light is analysed with a grating monochromator and detected with a Ge:Ga photoconductive detector cooled with liquid helium.

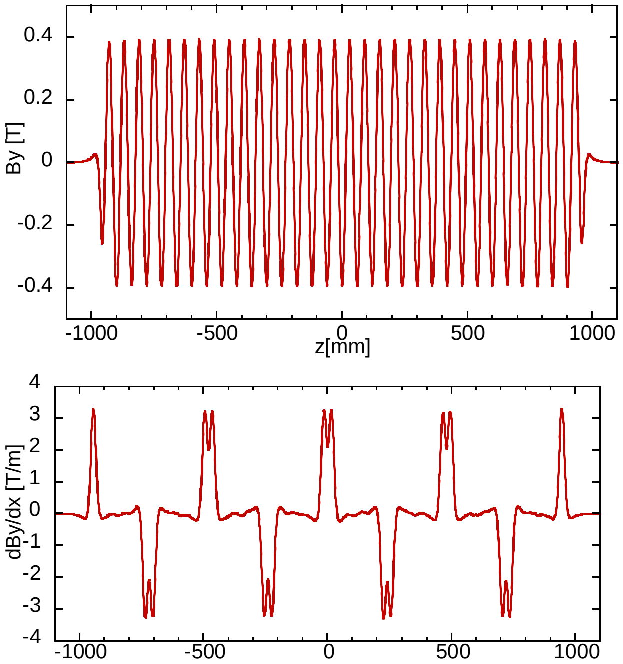

Fig. 5. Magnetic field and the field gradient in the vertical direction measured along the beam axis of the strong focus wiggler at the magnet gap of 3 cm.

SUMMARY

After a long period of suspension, the infrared FEL at ISIR, Osaka University is being commissioned. The linac has been largely remodelled, so that the FEL is expected to operate stably at the saturation power level, which was not possible before. The optical resonator and the measurement system have been aligned, the experiment is all set up, and we are waiting for the machine time for FEL.

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