

BUNCH LENGTH MEASUREMENTS AT LEBRA

K.Yokoyama ^{#,*,A)}, I.Sato ^{A)}, K.Hayakawa ^{A)}, T.Tanaka ^{A)}, Y.Hayakawa ^{A)}, K.Nakao ^{B)}

A) Laboratory for Electron Beam Research and Application, Institute of Quantum Science,
Nihon University 7-24-1 Narashinodai, Funabashi, 274-8501

B) College of Science and Technology, Nihon University
7-24-1 Narashinodai, Funabashi, 274 -8501 Japan

Abstract

The high-gain FEL amplification in near IR and SASE have been observed at LEBRA (Laboratory for Electron Beam Research and Application). A very short bunch of the electron beams have been achieved by the achromatic bending system, as the bunch compression system due to apt on the accelerating phase in the last accelerating section. The bunch length was estimated from the phase ellipse parameters which is deduced from the dependence of the beam spread on the accelerating phase. The bunch length of FWHM was estimated approximately 0.33 mm from the results of the experiments. Besides, the pulse length of the FEL lights around the wavelength of 1.5 micrometer was measured by means of the autocorrelation. The pulse length was less than 0.06 mm according to the number of interference waves. The pulse length of the FEL lights corresponds to around 20% of the electron bunch length.

INTRODUCTION

The high-gain FEL amplification has been obtained and the result of the simulation extracted from the FEL gain indicates that the bunch length could be around 1 ps or less [1]. SASE has also been observed using the electron beam with a low macropulse beam current and a very short bunch with considerable bunch compression in the achromatic bending system [2]. In order to investigate the bunch length which yields the high gain FEL amplification, the electron bunch length was measured by means of the simple theory about the phase ellipse instead of using a streak camera, which provides a direct and convenient way to measure bunch lengths but a high-accuracy one is very expensive. The pulse length of the FEL lights around the wavelength of 1.5 μm was also measured by means of the autocorrelation to compare the results of the bunch length.

The part of the main accelerating at LEBRA consists of three 4-m accelerating sections [3, 4]. The accelerating RF is provided by two 20-MW klystrons, which are operated at 2856 MHz with a pulse length 20 μs. The Phase flatness of the pulse error within 0.3° was achieved [5]. Klystron #1 is used for the injector and the first accelerating section and klystron #2 is used for the two accelerating sections. The electron beam accelerated in the linac is transported to the FEL system through the 90° achromatic bending and analyzer magnet system. The

energy spread of the beam is restricted to about 1% by a slit of the momentum analyzer. The FEL system consists of an undulator of 50 periods of a Halbach-type permanent magnet array and an optical cavity and the cavity length is about 7 m.

EXPERIMENTAL METHOD [6]

The input RF phase of klystron #2 and the accelerating phase in accelerating section #3 can be changed by two phase shifters independently as shown in Fig. 1. The energy spectrum can be obtained by utilizing the first 45° bending magnet of the momentum analyzer as a spectrometer. The bunch length was estimated from the energy spread by using the method as below.

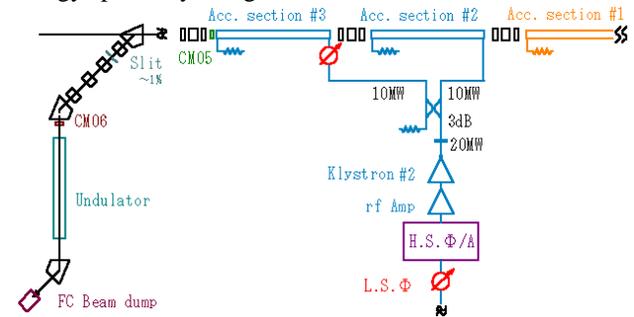


Figure 1: Layout of the FEL LINAC at LEBRA.

Maximum Energy Gain

The maximum electric field of the accelerating RF, E_p , is obtained from the maximum energy of the energy spectrum depending on the accelerating RF phase. E_0 is the total accelerating energy which beams obtain until acc-section #2 and the beam loading in acc-section #3, E_i is the beam energy after acc-section #3 and ϕ_i is the accelerating phase in acc-section #3. This correlation can be written

$$E_i = E_0 + E_p \cos\phi_i \quad (1)$$

where the original point of ϕ_i is based on the phase with the maximum energy. E_0 and E_p can be obtained by the least-square method from the experimental data of E_i and ϕ_i .

Ellipse Parameters

To describe a beam in phase space, assuming that the distribution of the beam at any other place along the transport line is to be an ellipse space, it can be expressed

$$\gamma_0 \Delta l^2 - 2\alpha_0 \Delta l \Delta E + \beta_0 \Delta E^2 = \epsilon \quad (2) [7]$$

[#]kazue.yokoyama@kek.jp

* Present affiliation: High Energy Accelerator Research Organization, KEK, 1-1 Oho, Tsukuba, 305-0801 Japan

where α_0 , β_0 , γ_0 and ε are ellipse parameters and $\sqrt{\varepsilon\beta_0}$ represents the bunch length and $\sqrt{\varepsilon\gamma_0}$ represents the energy spread of the electron beam.

The vector in the longitudinal phase space at the entrance of acc-section #2 can be represented as $(\Delta l_0, \Delta E_0)$ and it can be transferred to $(\Delta l, \Delta E)$ at the linac exit, the electron beam passing through acc-section #2 and #3. Δl_0 and ΔE_0 represent position and energy relative to the electron along the central orbit, respectively. The matrix formulation can be expressed by

$$\begin{pmatrix} \Delta l \\ \Delta E \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ g(\theta, \Delta\theta) & 1 \end{pmatrix} \begin{pmatrix} \Delta l_0 \\ \Delta E_0 \end{pmatrix} \quad (3)$$

By using the same transfer matrix, the ellipse parameters are transformed as

$$\begin{pmatrix} \beta & \alpha \\ \alpha & \gamma \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ g & 1 \end{pmatrix} \begin{pmatrix} \beta_0 & \alpha_0 \\ \alpha_0 & \gamma_0 \end{pmatrix} \begin{pmatrix} 1 & g \\ 0 & 1 \end{pmatrix} \quad (4)$$

Three equations below can be obtained from Eq.(4);

$$\alpha(g) = \beta_0 g(\theta, \Delta\theta) + \alpha_0 \quad (5)$$

$$\beta(g) = \beta_0 \quad (6)$$

$$\gamma(g) = \beta_0 g(\theta, \Delta\theta)^2 + 2\alpha_0 g(\theta, \Delta\theta) + \gamma_0 \quad (7)$$

where the accelerating phase in acc-section #3 is expressed as $\theta + \Delta\theta$ when θ represents the accelerating phase in acc-section #2 and V_2 represents the maximum energy gain of acc-section #2 and #3. Approximating by the first order, $g(\theta, \Delta\theta)$ can be defined as;

$$g(\theta, \Delta\theta) = -2V_2 \cos \frac{\Delta\theta}{2} \sin \left(\theta + \frac{\Delta\theta}{2} \right) \frac{2\pi}{\lambda} \quad (8)$$

At this time, Eq.(7) becomes Eq.(9) by multiplying both sides by ε because the energy spread is $\delta E = \sqrt{\varepsilon\gamma_0}$.

$$\delta E^2 = \varepsilon\beta_0 g(\theta, \Delta\theta)^2 + \varepsilon 2\alpha_0 g(\theta, \Delta\theta) + \varepsilon\gamma_0 \quad (9)$$

Hence, the whole electron beam can be described by knowing the ellipse parameters of Eq.(9) which are obtained from the energy spread as a function, $g(\theta, \Delta\theta)$, of θ and $\Delta\theta$ and the bunch length can be also calculated from Eq. (6).

Bunch Length Through the Analyzer System

The ellipse parameters are also transferred to Eq. (10) after the achromatic bending system;

$$\begin{pmatrix} \beta & \alpha \\ \alpha & \gamma \end{pmatrix} = \begin{pmatrix} 1 & h \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \beta(g) & \alpha(g) \\ \alpha(g) & \gamma(g) \end{pmatrix} \begin{pmatrix} 1 & 0 \\ h & 1 \end{pmatrix} \quad (10)$$

$$h \equiv \frac{2\rho(\vartheta - \sin\vartheta)}{E_M} = 0.00125 \quad (11)$$

where ρ is the orbital radius (550 mm) and ϑ is the bending angle (45°) and E_M is the central energy depending on the purpose of experiment, respectively. The matrix formulation Eq. (10) becomes;

$$\alpha' = \alpha(g) + h \cdot \gamma(g) \quad (12)$$

$$\beta' = \beta(g) + 2h \cdot \alpha(g) + h^2 \gamma(g) \quad (13)$$

$$\gamma' = \gamma(g) \quad (14)$$

These equations can be calculated from the ellipse parameters in Eq. (9) and Eq. (5), (6), (7). The bunch length through the achromatic bending system can be also calculated from Eq. (13).

To investigate the bunch length of the electron beam at FEL oscillation, the energy spectra with the same central energy, which means E_M is constant, depending on the combination of θ and $\Delta\theta$ are measured.

Autocorrelation Method

The pulse length of the FEL lights around the wavelength of $1.5 \mu\text{m}$ was measured by using the interferometer based on the autocorrelation [8]. The interferometer is a Michelson-Moley type, which consists of two beamsplitters, a movable mirror and a fixed mirror as shown in Fig. 2. The interferogram is derived from the difference in path length between the light pulses split into two by a beamsplitter1 which works as a half mirror around $1.5 \mu\text{m}$. Detector1 measures a fundamental light of the FEL and Detector2 is used for a reference. The movable mirror can move in steps of $0.1 \mu\text{m}$. The optical pulse length is roughly estimated from multiplying the number of the interference wave by the half of the FEL wavelength.

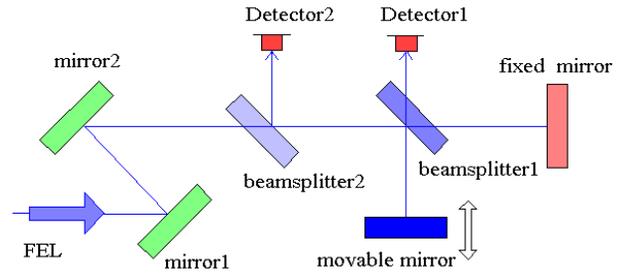


Figure 2: Layout of the interferometer.

RESULTS AND DISCUSSION

Electron Bunch Length

The result of the peak energy extracted from the energy spectrum as a function of the accelerating phase on acc-section #3 is shown in Fig. 3. Applying the least-square method, Eq. (1) was obtained as;

$$E_i = 62.02 + 40.35 \cos(\phi_i - 70) \quad (15)$$

where $E_p = 40.35$ comes from the result. The value of E_p corresponds to V_2 in the Eq. (8).

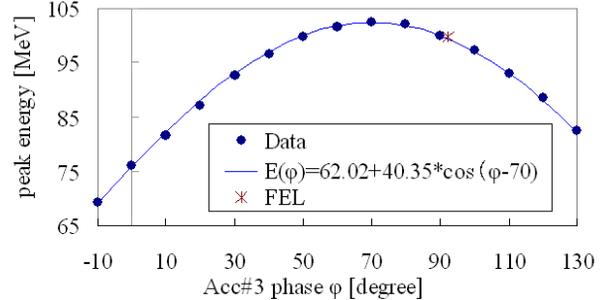


Figure 3: The electron peak energy depends on the accelerating phase. (* means the point of the observation of the maximum FEL power).

The energy spread extracted from energy spectrum which measured was by changing the accelerating phase are shown in Fig. 4. From fitting experimental data,

$$\delta E^2 = 1.94 \times 10^{-7} g(\phi)^2 + 2.75 \times 10^{-4} g(\phi) + 0.397 \quad (16)$$

was obtained. The bunch length (FWHM) at the linac exit is 0.88 mm (2.9 ps) from $2\sqrt{\epsilon\beta_0}$ given by Eq. (6).

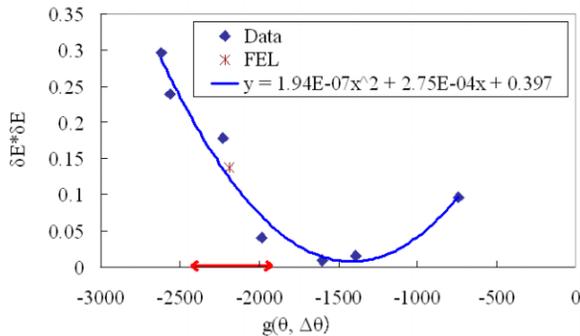


Figure 4: $g(\theta, \Delta\theta)$ and δE^2 as a function of accelerating phase and the ellipse parameters. (* means the point of the observation of the maximum FEL power. \leftrightarrow means the region of the FEL observed.).

Figure 5 shows the bunch length and the energy spread of the electron beam which supplied to FEL system. The central energy E_M is around 100 MeV and the macropulse current is about 80 mA. The point of (*) means the experimental data of which the highest power of the FEL was observed. The FEL gain was around 9% and the power was approximately 8 mJ/macropulse. The energy spread is 0.74% and the bunch length is 0.33 mm (1.1 ps) at this time. The peak current is expected to be 20 A or more.

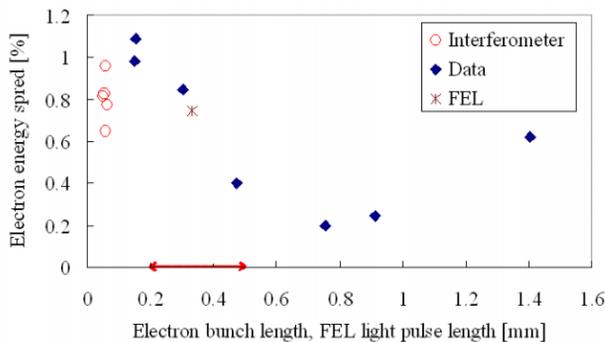


Figure 5: Electron bunch length and pulse length of the FEL light depending on the electron beam energy spread (FWHM). (* and \leftrightarrow mean the same as Fig. 4.).

Optical Pulse Length

The typical interferogram of the autocorrelation is shown in Fig. 6. The experimental beam parameter is the same as the bunch length measurements and the FEL wavelength is around 1.5 μm (3rd: 512 nm). The pulse length of the FEL light depending on the accelerating phase was measured when the FEL power is strong enough to get the interference wave from 5 to 8 mJ/macropulse. The results were shown in Fig. 5. The pulse length of the FEL light is around 0.06 mm (0.2 ps). The optical pulse length is 20% or less of the electron bunch length from the experimental results. The distribution of the electron beam which is high-density and attributable to the FEL oscillation could be narrow as interacting with

the optical pulse emitted from the electrons in the undulator.

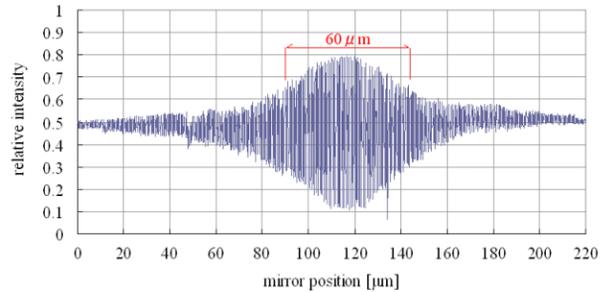


Figure 6: The typical interferogram of the autocorrelation.

CONCLUSION

It was confirmed experimentally that the bunch length at the FEL oscillation was 0.6-1.7 ps, by measuring the energy spread vs accelerating phase. The bunch length of the electron beam at the high-gain FEL amplification was around 1ps. This experimental result is consistent with the simulation [1].

The pulse length of the FEL light was extremely narrow to compare with the electron bunch length. The simulation about the correlation between the bunch length of the electron beam and the pulse length of the FEL light has proceeded at LEBRA.

REFERENCES

- [1] Y.Hayakawa et al., "Characteristics of the Fundamental and 3rd Harmonic FEL at LEBRA", Nucl. Instr. and Meth. A507 (2003) 404.
- [2] T.Tanaka et al., "Observation of SASE in LEBRA FEL system", To be published in Nucl. Instr. and Meth. A, Proc. of the 25th International Free Electron Laser Conference and 10th FEL Users Workshop (Tsukuba, Ibaraki, Japan, Sep.8-12, 2003).
- [3] K.Hayakawa et al., "Performance of the FEL Linac at Nihon University", Proc. of this Conf.
- [4] T.Tanaka et al., Proc. of the 1st Asian Particle Accelerator Conference (1998) 722.
- [5] K.Yokoyama et al., "Improvement of the PFN Control system for the Klystron Pulse Modulator at LEBRA", To be published in Nucl. Instr. and Meth. A, Proc. of the 25th International Free Electron Laser Conference and 10th FEL Users Workshop (Tsukuba, Ibaraki, Japan, Sep.8-12, 2003).
- [6] D.H.Dowell et al., "Longitudinal emittance measurements at the SLAC gun test facility", Nucl. Instr. and Meth. A507 (2003) 331.
- [7] H.Wiedemann, Particle Accelerator Physics 1, Springer (1993) 152.
- [8] C.Settakorn et al., "Impact of Experimental Conditions on Autocorrelation Bunchlength measurements", Proc. of the 2nd APAC, Beijing, China, 2001, p.728.