Bright electron multi-bunch production for the high power JAERI-FEL oscillator

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Abstract

Stable and bright electron multi-bunches at 16.5 MeV with a long macro-pulse duration over 0.4 ms, which consists of 4,000 micro-bunches, have been produced at the Japan Atomic Energy Research Institute (JAERI) superconducting linac driven Free-Electron Laser (FEL) facility. The bunch charge is 0.5 nC with peak current higher than 100 A. The bright electron bunch was generated using a RF compression made in two stages in the injector system, and directly led to a quasi-CW kilowatt lasing. In this paper, we describe the bunching system and electron beam performances in JAERI-FEL.

1 INTRODUCTION

A Free-Electron Laser (FEL) oscillator has been developed as a high-power light source for industrial processing [1]. In FEL oscillators, undulator radiation stored in an optical cavity is amplified through an FEL interaction with successive fresh electron bunches. An optimum cavity length and the stability of electron bunch intervals are therefore required for FEL oscillators. The lasing dynamics of FEL oscillators depends on the detuning length (δL) of the optical cavity from the perfect synchronism ($\delta L = 0$), where the cavity length is completely matched with the electron bunch interval. An efficiency curve as a function of δL is antisymmetric with respect to $\delta L = 0$. The efficiency becomes maximum near $\delta L = 0$ and steeply drops to 0 at slightly longer cavity length [1, 2]. The high power FEL operation near $\delta L = 0$ is therefore especially sensitive to the stability of the bunch intervals. The gain and efficiency increases with increasing dimensionless beam current j_0 [3], which is proportional to the peak current of the bunch. A bunching system to realize the high peak current is necessary for the high power FEL operation. A long macro-pulse is also indispensable to reach saturation near $\delta L = 0$, because the gain is small near $\delta L = 0$ and many round-trip times are required. A superconducting linac, which is a driver for JAERI-FEL, can produce electron multi-bunches with a long macro-pulse duration and is most suitable for the high power FEL operation.

Recently a sustained lasing at $\delta L = 0$ with efficiency over 6 % was demonstrated in the JAERI-FEL oscillator for the first time [4]. The high efficiency FEL is due to the stable electron multi-bunch production over 0.4 ms with a peak current higher than 100 A. In this paper, we describe the injection system for the bright electron bunch production and electron beam performances.

2 INJECTOR SYSTEM FOR FEL OSCILLATORS

Two sorts of injector systems are used for the production of longitudinally bright electron bunches. One is a photocathode RF gun system, and the other is a injector system consisting of a DC gun, a sub-harmonic buncher (SHB) for bunch compression, and a buncher for increasing the energy and further compression. Photocathode RF guns are used in many FEL oscillators [5], and are useful devices for their compactness and low transversal emittance. The progress of them is however underway and they have not been used as injectors for user facilities, yet. In this paper, the latter case used in the JAERI-FEL facility is studied.

There are three major FEL user facilities driven by normal conducting linacs: FELIX [6], CLIO [7], and FELI [8]. Their frequencies of accelerators are around 3 GHz, and injector systems are similar to each other. In FELIX, the injector system consists of a DC gun with a thermionic cathode operated at 100 kV, a SHB at frequency of 1 GHz with a drift space of 21 cm, and a fundamental buncher at frequency of 3 GHz. The bunch charge is 0.22 nC, and the initial width is 0.28 ns FWHM, which corresponds to 50 degree for SHB and is enough short to capture almost the whole bunch in the injector system. In CLIO, components are similar to FELIX, except for the initial bunch width of 1 ns, the charge of 1 nC, and the frequency of 500 MHz of a SHB. The initial bunch width corresponds to 160 degree for the SHB and is too long to capture the bunch fully in the injector system. A satellite pulse observed in CLIO indicates the long duration of the initial bunch [7]. In FELI, the injection system is also similar to FELIX or CLIO, but a similar problem to CLIO exists in the injector system. The initial bunch width corresponds to 128 degree for the SHB and is too long to capture the whole bunch in the injector system, and about a half of the bunch can be only transported through the accelerator. The common feature of bunching schemes for the above three FELs is a short drift length after the SHB to reduce the space charge effects in the low energy region.

Different from normal conducting linac driven FELs, superconducting linac driven FELs are limited to a few facilities. Their designs of injector systems are quite different from each other. In the Stanford FEL center, the injector system consists of a DC gun operated at 120 kV with a thermionic cathode, a SHB at frequency of 230 MHz with a drift space of 3.8 m, and a capture section at frequency of 1.3 GHz where the first seven-cell are cavities for β = 0.95, and the succeeding single-cell accelerator of 3.8 m long is also used to accelerate the bunch. The initial width of the bunch is 0.5 ns FWHM with 0.021 nC, which corresponds to 41 degree for the SHB. The unique feature in Stanford is the long drift space after the SHB. The bunch compression using a SHB at a lower frequency with a long drift space is preferred, if the space charge effect is not so serious, because the capture of the bunch is easier when the initial pulse width is enough short against a half cycle of the SHB. The Thomas Jefferson National Accelerator Facility (TJNAF) equips a novel photocathode DC gun driven by a Nd:YLF laser. The high voltage of the gun is 350 kV. The pulse width from the gun is 40 ps, which is enough short for the fundamental frequency of 1.5 GHz. The bunch is compressed by a buncher of a frequency of 1.5 GHz with a drift space of 1 m and accelerated up to 10 MeV by a superconducting cavity. The final bunch width in the undulator is less than 1 ps. The unique feature in TJNAF is the short initial pulse width from the gun with a high voltage which is efficient to reduce the space charge effect.

3 INJECTOR SYSTEM IN JAERI-FEL

JAERI-FEL is also driven by superconducting accelerators, and its injection system is quite different from others. The bunch charge of 0.5 nC is comparable with FELIX, CLIO, and FELI, but over eight times higher than TJNAF, and Stanford. The initial width of the bunch is 0.8 ns FWHM, which is comparable with CLIO, FELI, and Stanford. A SHB at a high frequency with a short drift space is not appropriate to capture the bunch effectively, while a long drift space should be avoided to reduce the space charge effect due to the high bunch charge of 0.5 nC. Fortunately, the JAERI-FEL facility has some unique features from its original construction. They are a low fundamental frequency of 499.8 MHz for accelerators, a low frequency of 83.3 MHz for a SHB, and a high voltage of 230 kV for a DC gun with a thermionic cathode. The lower frequencies are useful to capture the bunch effectively, and the high voltage of the gun is useful to reduce the space charge effect, even if the drift space is long like Stanford case. In addition, the capture section is consisted of separately controlled two single-cell accelerators and a drift space of 11 m long. The main bunch compression is made in this capture section at the beam energy of 2.3 MeV.

Figure 1 shows the layout of the JAERI-FEL facility. The electron bunch is produced by the gun at the energy of 230 keV. The details of the gun performance are described in Ref. [9]. A unique feature is its low time jitter less than 15 ps rms over a macropulse duration. The effect of the time jitter of the gun remains after the acceleration and causes the fluctuation of the bunch interval, which reduces the FEL efficiency. In JAERI-FEL, the bunch is compressed from 800 ps to 5 ps, and the jitter in the undulator is estimated to be less than 100 fs.

The bunch width of 0.8 ns corresponds to 24 degree for the SHB, and is compressed to about 100 ps FWHM at the entrance of the first single-cell accelerator without any loss. The drift length of 4.5 m after the SHB has been optimized for an effective compression, already [9]. The bunch in the low β region slips from the initial acceleration phase given at an entrance of a cavity through the passage, if the cavity is designed for the electron beam of $\beta = 1$. In order to avoid the slip effect, the bunch should be accelerated up to the energy around $\beta = 1$ in the early stage of the acceleration. The main role of the first single-cell accelerator is to accelerate the bunch up to the energy around 1.3 MeV where $\beta = 0.96$.

The bunch after the first single-cell accelerator can be rotated in the longitudinal phase space by setting the phase of the second single-cell accelerator to a optimum bunching phase, because the effect of the slip in a cavity is small, and the bunch becomes upright at the entrance of the first five-cell accelerator after the drift space of 11 m long. Each five-cell accelerator gives the 7 MeV energy gain, and the final energy of the electron beam reaches 16.5 MeV. The electron beam is transported into the undulator through a 180 degree achromatic and isochronous bending magnet system and stopped at the beam dump.

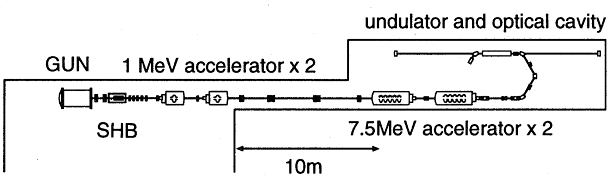

Figure 1: Layout of the JAERI FEL facility.

4 ELECTRON BEAM PERFORMANCE IN JAERI-FEL

The longitudinal bunch shape is measured by using a synchroscan streak unit (Hamamatsu M1954-10) and OTR from an aluminum screen at the center of the undulator. During the measurement the macro-pulse length is set to 200 μs to avoid an unnecessary radiation and the gate for the measurement is opened from 100 μs to 200 μs, because amplitudes and phases of accelerators are slowly changing for the first several tens micro seconds by a feedback loop.

The minimum bunch width obtained from the experiment is 5 ps as shown in Fig. 2, and is almost comparable with the trigger jitter of the synchroscan streak camera. The time scale was precisely calibrated by using a trombone. The peak current required by a simulation to reproduce the FEL efficiency curve shown in Fig. 3 is around 120 A with assumption of triangular shape of the bunch [10], and is almost equal to the experimental value.

The time jitter inside the undulator can be estimated from the jitter at the gun, but the efficiency curve is also used to estimate the jitter. Figure 3 is a typical experimental result of the efficiency curve as a function of δL. The width of the sharp peak at $\delta L = 0$ is about 1 μm. A shift of $\delta L = 1$ μm corresponds to 25 μm shift of an FEL light until the FEL power decreases to 1/e, because a optical cavity

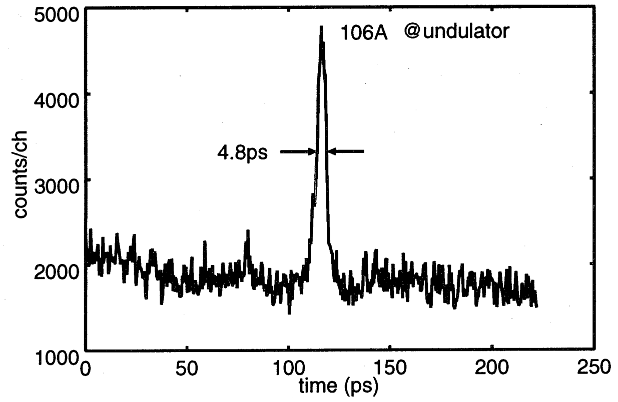

Figure 2: A synchroscan streak camera signal obtained at the center of the undulator.

loss is measured as 8 % in the experiment. The time jitter of 100 fs of the bunch, which is almost equal to the jitter estimated from the gun jitter, corresponds to the fluctuation of 30 μm. The sharp peak therefore would be dull with the jitter larger than 100 fs. A simulation also shows that the jitter is less than 100 fs to reproduce the efficiency curve observed in JAERI-FEL [10]. Table 1 shows all the beam performances of JAERI-FEL after the whole acceleration.

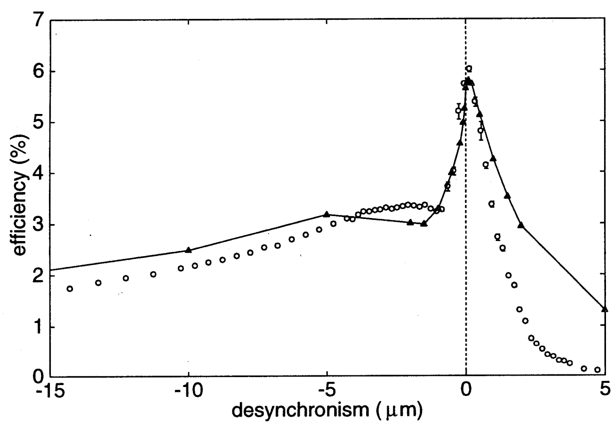

Figure 3: The open-circles are typical efficiencies as a function of detuning length in JAERI-FEL [4]. The solid-triangles are our numerical results [10], which agree with the measured efficiency curve well. The solid-line is a guide to the eye.

5 SUMMARY

We succeeded in producing the electron bunch with 1.5 mm long and peak current higher than 100 A, and placing the successive bunches with the interval of 28.8 m within the accuracy of 30 μm in a longitudinal direction over 4,000 multi-bunches. The multi-bunches satisfy performances required for high power FEL oscillators: stability of bunch interval, high peak current, and long macropulse duration. The stable and bright multi-bunches led to a high efficiency FEL operation at the perfect synchronism in JAERI-FEL.

Table 1: Performance of the electron bunch at JAERI-FEL

Parameter	Measured
Micropulse repetition	10.4125 MHz
Macropulse length	up to 1 ms
Macropulse repetition	10 Hz
Peak current	> 100 A
Pulse width (FWHM)	< 5 ps
Bunch charge	0.5 nC
Time jitter (rms)	< 100 fs
Normalized emittance	20(y),40(x) mm-mrad
Energy	16.5 MeV
Energy spread (rms)	< 1.2 %

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