VUV SEEDED FEL EXPERIMENT AT THE SCSS TEST ACCELERATOR

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Abstract

A short wavelength seeded FEL has been demonstrated at the SCSS test accelerator using high-order harmonics generated in gas of a titanium-sapphire laser as an external seed source. After the improvement of the accelerator stability and undulator magnetic errors in 2007, the FEL gain was drastically increased and detailed measurements have been carried out particularly on the spectral characteristics of the seeded FEL. Although the wavelength of the seed is 160 nm for the moment, we have succeeded to observe nonlinear harmonics of the FEL fundamental wavelength including both odd and even harmonics. It leads to the development of a short wavelength seeded FEL. Currently we are working on the modification of the seeding system in order to reach a 50-60 nm range using high-order harmonics of the plateau region. By combining a short wavelength seed with nonlinear harmonics, a seeded FEL below 10 nm becomes feasible.

INTRODUCTION

A linear accelerator (LINAC) based free electron laser (FEL) is one of the most promising candidates of short wavelength coherent light sources in the wavelength range from VUV to X-rays. Since no practical mirrors are available in these short wavelengths to compose an optical cavity, the light is amplified by single pass in undulators. There are three major projects of the X-ray FEL currently in progress, the XFEL of SPring-8 in Japan [1], LCLS of SLAC in the U.S. [2] and the European XFEL of DESY in Germany [3], and these FELs are based on self-amplified spontaneous emission (SASE). Since SASE uses stimulated emission from the electron beam [4], significantly higher peak power can be obtained compared to conventional synchrotron radiation sources, that are spontaneous emission. However as well known, the spectrum and temporal intensity distribution of the SASE pulse contains a spiky structure, which is randomly changed from pulse to pulse [5]. Although this characteristic of the SASE pulse may not hinder applications using a whole SASE spectrum, the intensity fluctuation becomes much larger once a part of the spectrum is selected out by a narrow band monochromator.

This random spiky structure of SASE comes from its short temporal coherent length compared to the pulse duration due to the lack of the longitudinal mode selection by an optical cavity. In order to solve this problem, a regularly spaced modulation at the radiation wavelength should be given to the electron beam. One way to achieve this is the injection of external coherent seed light, that is a seeded FEL [6].

In 2006, the SCSS (SPring-8 Compact SASE Source) test accelerator was constructed in SPring-8 as a test facility of the XFEL project. In 2007, the saturation of SASE was achieved in the wavelength range from 50 nm to 60 nm, and the facility is now open to user experiments [7].

A seeded FEL configuration has been demonstrated at this SCSS test accelerator. In the seeding experiment, high-order harmonics generation in gas (HHG) is used as an external coherent seed source [8]. Different from the harmonic generation in solid crystals showing serious absorption at short wavelengths, the wavelength of HHG can go down to a few nm keeping good coherent properties. Currently the 5th harmonic of a titanium-sapphire laser is used as seed light, but we are planning to go around 60 nm in future experiments.

EXPERIMENTAL SET UP

SCSS Test Accelerator

Fig. 1 is a schematic of the SCSS test accelerator. The machine parameters for the seeded FEL experiments are listed in Table 1. Total length of the facility is about 60 m and there are two undulators whose gap can be independently changed. Nominal beam energy of the SCSS test accelerator is 250 MeV, but it is reduced to 150 MeV by switching off two C-band accelerators for the seeded FEL experiments.

Timing System

The titanium-sapphire laser system is installed outside the accelerator tunnel. The system consists of an oscillator (79 MHz), a regenerative amplifier (800 Hz) and a multi-pass amplifier (10 Hz). The oscillator is mode-locked to the external 79 MHz signal generated from the accelerator 238 MHz RF source. Since the SCSS test accelerator is operated in synchronization with a 60 Hz power line for stable acceleration of the electron bunches, the intervals

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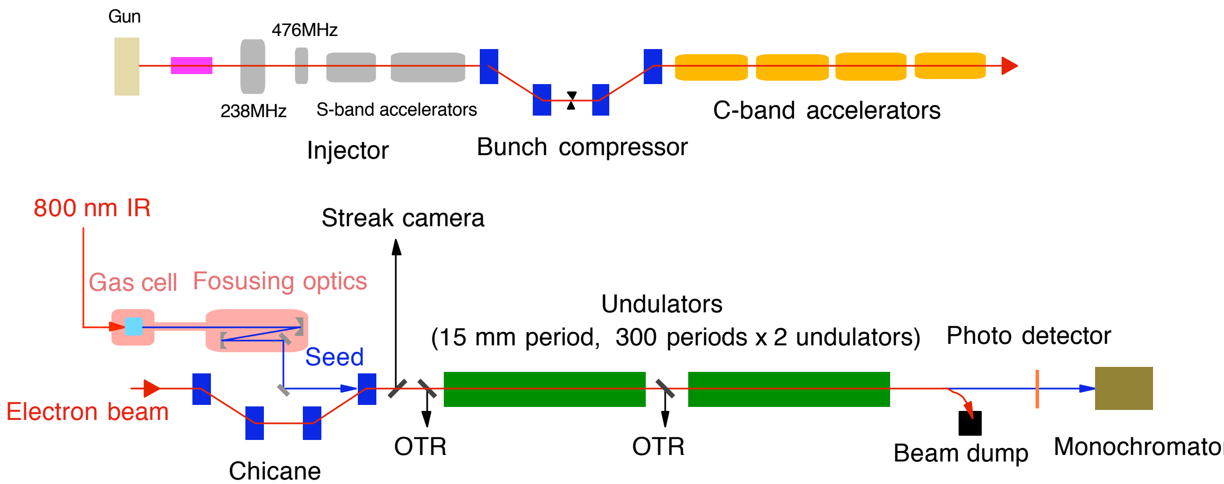

Figure 1: Schematic of the SCSS test accelerator.

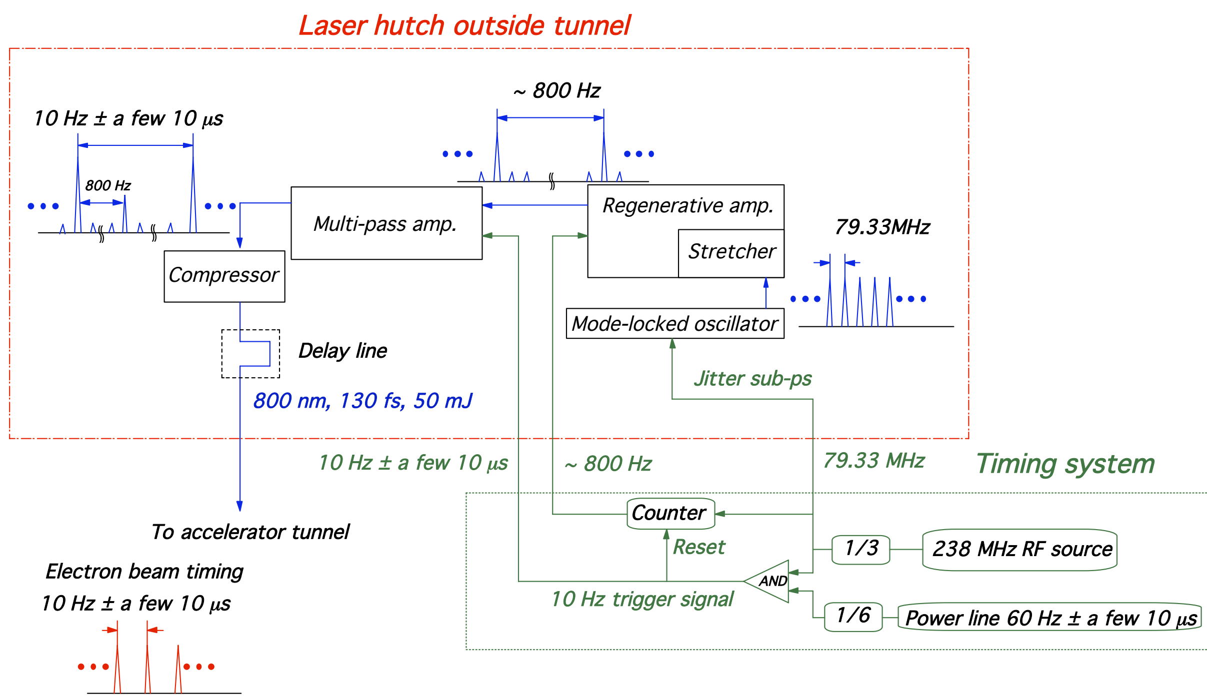

Figure 2: Synchronization system of the titanium-sapphire laser to the electron beam.

Table 1: Parameters of the SCSS test accelerator for the seeded FEL experiment

Beam energy	150 MeV
Bunch charge	0.2 ~ 0.3 nC
Bunch length	0.7 or 4 ps (FWHM)
Slice emittance	~ 0.7 πmm-mrad
Beam repetition	10 Hz
Seed wavelength	160 nm
Undulator period	15 mm
Undulator K value	1.3

between bunches are not equal but change by a few tens of μsec due to the frequency fluctuation of the 60 Hz power line. Therefore, the right laser pulse from the oscillator should be selected and amplified in the two-stage amplifier in synchronization with the electron bunch timing. The electron bunch timing is sent by a 10 Hz trigger signal arriving 15 ms before the beam emission from the gun. Since the 10 Hz trigger signal has a jitter of a few 10 μs, the timing of the 800 Hz regenerative amplifier is readjusted for each electron bunch by resetting a 79 MHz RF counter with the 10 Hz trigger signal. The 10 Hz multi-pass amplifier is directly synchronized with the 10 Hz trigger signal. Fig. 2 summarizes the timing system employed for the seeding experiments.

At the end of the titanium-sapphire laser system, 800 nm laser pulses are amplified up to 50 mJ with a pulse duration of 130 fs and 10 Hz repetition rate. The measured jitter of the 800 nm laser pulse with respect to the electron bunch is about 1.3 ps (rms).

Generation of the Seed

The 800 nm laser pulses of the titanium sapphire laser system are sent to the accelerator tunnel through a vacuum transport line. The 800 nm light is focused in a gas cell for HHG. The gas medium used for the 160 nm seed generation is xeon. After the gas cell, vacuum chambers housing two focusing and two steering mirrors are installed with a differential pumping part. The two focusing mirrors are placed first and they are made of SiC to avoid a damage due to the 800 nm laser pulse. The plane multi-layer mirrors are used as steering mirrors to obtain higher reflectivity for the 160 nm seed, and at the same time most of the 800 nm component is removed.

In the SCSS test accelerator, there is a chicane with four bending magnets upstream of the undulators (Fig. 1), and the seed pulse and the electron bunch are overlapped at the end of the 4th bending magnet of the chicane.

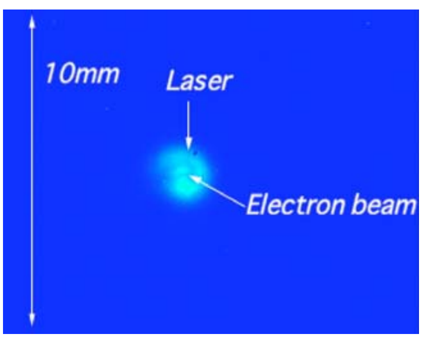

Figure 3: Transverse overlap between the 800 nm laser and the electron beam observed on the OTR screen.

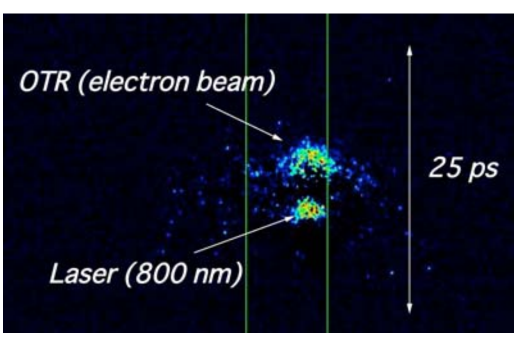

Figure 4: Longitudinal position of the 800 nm laser and the electron bunch measured with a streak camera. Two pulses are intentionally displaced in the figure.

Overlap Between the Seed Pulse and the Electron Bunch

In the seeded FEL, the seed pulse and the electron bunch should be precisely overlapped in a 6-dimensional phase space, namely positions and angles in two transverse directions, time and energy. Since the interaction between the seed and the electron beam is mainly occurred in the first undulator, the focusing optics of the seed pulse is designed so that the envelop of the seed light has a waist at the middle of the first undulator.

The transverse overlap is confirmed on optical transition radiation (OTR) screens located at the entry and exit of the first undulator. These OTR screens are made of gold mirrors to measure the transverse position of the electron beam. But at the same time, residual 800 nm laser pulse, with which the seed pulse takes the same path, can be observed on the same OTR screens. Fig. 3 is the observed image of the 800 nm laser and the electron bunch on the OTR screen.

In the longitudinal dimension, a streak camera is used to check the temporal synchronization. The OTR screen for temporal measurement is installed at the upstream of the first undulator (Fig.1). The OTR generated from the electron bunch and the 800 nm laser pulse are sent together along the same path to the streak camera located outside the accelerator tunnel. Since the OTR contains wide spectral components, the resolution of the streak camera is limited to a few ps due to chromatic aberration. Therefore after the streak camera measurement, the synchronization is finely adjusted with an optical delay line by monitoring the seed amplification.

The wavelengths of the seed and the spontaneous radiation from the undulators are directly measured and compared on a monochromator. Then the undulator K-value is adjusted to match them.

SPECTRUM IMPROVEMENT BY THE SEEDED FEL

Large Gain Case

The spectra of the seeded FEL are shown in Fig. 5. After one undulator, a single peak spectrum was obtained at the same wavelength of the seed with a narrower spectral bandwidth.

Although the seed injection does not increase the FEL gain or the saturation power, the amplification starts from higher power level compared to SASE starting from the noise. As a result, the seeded FEL saturates in a shorter undulator length than SASE.

In the current experimental condition, the duration of the seed pulse is shorter than the electron bunch length. The pulse duration of the seed is estimated to be about 60 fs (FWHM) from its spectral width and the electron bunch length is about 700 fs (FWHM). Therefore only 10 % of the electrons is overlapped with the seed. In this condition, the amplified seed by the overlapped electrons reaches saturation first, and then SASE from the rest of the electrons saturates later.

As shown in the Fig. 5, several peaks appear in the spectrum of the seeded FEL after the second undulator due to the increased power of SASE. In addition, the central wavelength of the seeded FEL shifts to the longer wavelength compared to the original seed wavelength.

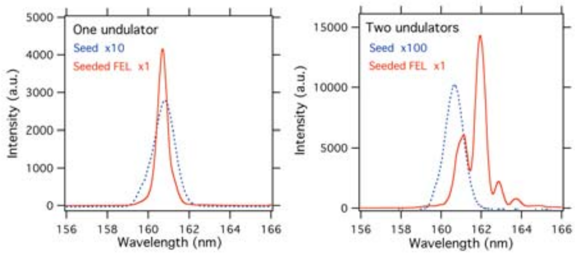

Figure 5: Spectra of the seeded FEL with large FEL gain, left: after the first undulator, right: after the second undulator. Lines in red are the spectra of the seeded FEL and blue dotted lines are those of the seed.

Small Gain Case

In this measurement, inverse energy chirp was given to the electron bunch, namely higher beam energy at head and lower energy at tail, by placing the electron bunch on the opposite side of the RF crest of the S-band accelerator. When this electron bunch with inverse energy chirp passes the bunch compressor, the electron bunch length is stretched to about 4 ps (FWHM) and the peak current and the FEL gain are reduced.

Figs. 6 and 7 are the measured spectra of the seeded FEL and SASE after the first and second undulator with the reduced FEL gain respectively. Although the spectrum of the seeded FEL is slightly affected by SASE, it keeps a single peak after the second undulator as shown in Fig. 7. Since the FEL gain is low, the SASE power is still small compared to the amplified seed even after the second undulator.

The integrated pulse energies over the spectrum are estimated to be about 540 nJ and 160 nJ for the seeded FEL and the SASE pulses shown in Fig. 7.

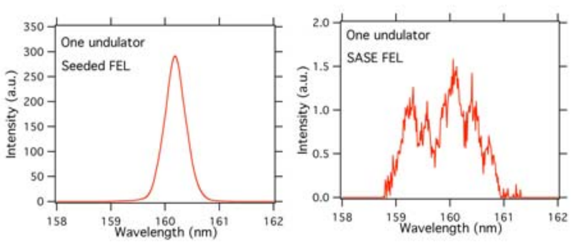

Figure 6: Spectra of the seeded FEL and SASE with small FEL gain after the first undulator, left: seeded FEL, right: SASE.

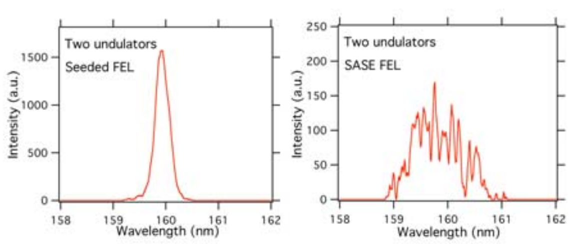

Figure 7: Spectra of the seeded FEL and SASE with small FEL gain after the second undulator, left: seeded FEL, right: SASE.

STABILIZATION OF THE CENTRAL WAVELENGTH

Fig. 8 displays how the central wavelength of the seeded FEL changes according to the undulator gap [9]. In the measurement of Fig. 8, the electron bunch length was 4 ps and only the first undulator gap was closed. The central wavelength of SASE changes almost linearly as a function of the undulator gap. On the other hand, the central wavelength of the seeded FEL is fixed at the seed wavelength within the FEL gain bandwidth even if the undulator gap is slightly detuned from the resonance condition.

The undulator gap was changed in Fig. 8, but the same holds true for the beam energy. The seeded FEL is expected to stabilize the central wavelength also against the beam energy fluctuation.

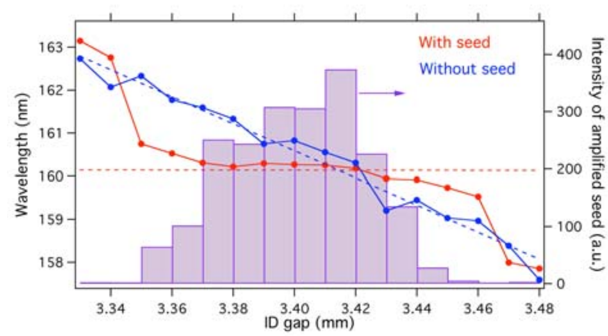

Figure 8: Central wavelengths of the seeded FEL (line-points in red) and SASE (line-points in blue) as a function of the undulator gap. Black dashed line is the wavelength of the seed. Bars show the intensity of the seeded FEL. The electron bunch length is 4 ps and only the first undulator gap is closed

NONLINEAR HARMONICS OF THE SEEDED FEL

Nonlinear harmonics (NLH) of the seeded FEL were observed including odd and even harmonics except 4th. The 4th harmonic could not be observed due to poor diffraction efficiency of the monochromator.

Fig. 9 shows the spectra of the 3rd harmonics measured with a 4 ps electron bunch after the first undulator. The intensity increase at long wavelengths in the specrum of the seeded FEL (Fig. 9, left) is due to stray light of the 800 nm laser. Both the seeded FEL and the SASE spectra are mainly spontaneous emission and the intensities are similar.

In contrast, the spectrum of the seeded FEL after the second undulator showed rapid evolution of the 3rd harmonics as shown in Fig. 10. While the SASE spectrum after the second undulator holds the same shape and the intensity is increased just by a factor of two, nonlinear amplification occurs for the seeded FEL.

Fig. 11 is the spectrum of the 5th harmonics of the seeded FEL. The intensity of SASE was too small to measure a spectrum. Note that the spectrum width of Fig.

11 is somehow broadened due to the monochromator resolution.

In order to pursue short wavelengths, these higher harmonics are important not only as a light source for users, but also as a coherent seed source, for example in high gain harmonic generation (HGHG) [10].

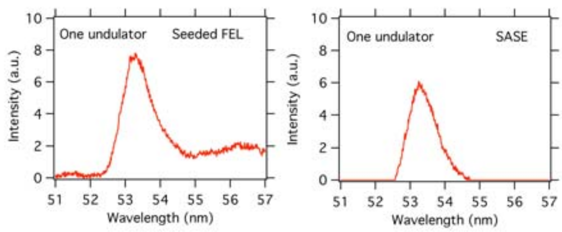

Figure 9: Spectra of 3rd harmonics of the seeded FEL and SASE after the first undulator, left: seeded FEL, right: SASE. The electron bunch length is 4 ps and the spectra are mainly spontaneous emission. The intensity increase at the long wavelngths in the spectrum of the seeded FEL is due to stray light of 800 nm laser.

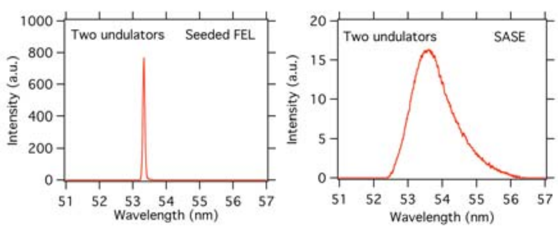

Figure 10: Spectra of 3rd harmonics of the seeded FEL and SASE after the second undulator, left: seeded FEL, right: SASE. The electron bunch length is 4 ps and the SASE spectrum is mainly spontaneous emission.

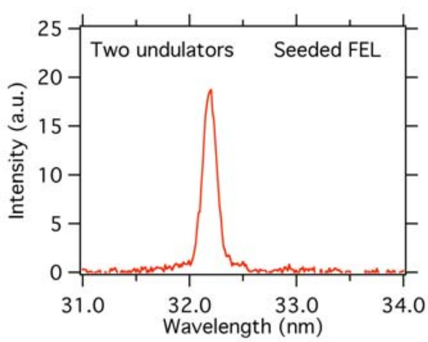

Figure 11: Spectrum of 5th harmonics of the seeded FEL, the electron bunch length is 4 ps.

FUTURE PLANS

At the SCSS test accelerator, we are planning to provide the light of the seeded FEL to user experiments. For that, several technical issues should be improved.

In the current seeding expriment, the beam energy is decreased to 150 MeV from the nominal energy of 250 MeV. This is because the pulse energy of HHG at 60 nm is too small for the seeding with the current experimental set up. The focusing optics of 800 nm should be optimized and the improvement of mirror reflectivity for the HHG seed is necessary by using multilayer mirrors.

At the same time, the stability of the synchronization between the seed pulse and the electron bunch are not stable enough. The oscillator of the titanium sapphire laser is locked to the 79 MHz RF signal generated from the 238 MHz accelerator clock as shown in Fig.2. In order to reduce temporal jitter, the use of a higher frequency has an advantage in view of noise. In a new synchronization system, a fast photo-detector will be employed to detect the higher harmonic component of the oscillator laser pulses. Then the phase of the laser pulses is directly compared to the accelerator RF signal of higher frequency. In addition, IQ detection (In-phase and Quadrature-phase detection) will be also introduced, with which the electron beam jitter with respect to the accelerator RF clock has been successfully measured with a precision less than 50 fs in the SCSS test accelerator [11]. Different from a conventional phase lock loop, the phase and amplitude can be detected simultaneously in the IQ detection. Therefore the effect of the amplitude fluctuation of the photo-detector signal can be cancelled for the phase detection.

SUMMARY

A VUV seeded FEL has been successfully demonstrated at the SCSS test accelerator using the seed of HHG. Since the spectral characteristic of the seeded FEL is the most important advantage compared to SASE, it has been investigated experimentally in detail. The spectrum of the seeded FEL depends on various parameters such as the FEL parameters, the undulator length, the seed pulse duration and intensity. As shown in Fig. 5, the optimization of these parameters are necessary in order to fully benefit from the seeding effect. These experimentally observed spectral characteristics of the seeded FEL are well reproduced in a 3D FEL simulation by SIMPLEX [12], which will be published elsewhere.

As well known, the HHG shows a plateau region down to the cut off wavelength below 10 nm. Since the intensity of HHG does not decrease as a harmonic number in the plateau region, in principle, the seeded FEL using the HHG can be directly extended to shorter wavelengths close to the water window. Although a scheme like HGHG should be combined to reach the X-ray region, the shorter onset wavelength of the seed simplifies the FEL system and reduces the number of undulators.

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