EVOLVEMENT OF THE LASER AND SYNCHRONIZATION SYSTEM FOR THE SHANGHAI DUV-FEL TEST FACILITY*

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Abstract

Many attractive experiments including HGHG, EEHG, cascaded HGHG, chirped pulse amplification etc. are carried out or planned on the Shanghai Deep- Ultraviolet Free-Electron Laser test facility. These experiments are all utilizing a laser as seed, and need precise synchronization between the electron beam and the laser pulse. We will describe the history and current status of the seeding and synchronization scheme for the SDUV-FEL together with some related measurement results in this paper.

INTRODUCTION

High gain free-electron lasers (FELs) are being developed to serve as high-intensity coherent radiation sources for advanced user applications. One of the most feasible ways for delivering short-wavelength FEL is self-amplified spontaneous emission (SASE) [1, 2]. However, SASE radiation starts from shot noise of the electron beam, and results in a poor temporal coherence. With the growing interest in fully coherent sources, various seeded FEL schemes have been proposed on the basis of harmonic generation and seeding of external lasers. A typical scheme is high-gain harmonic generation (HGHG) [3], which has been demonstrated from the infrared to the soft X-ray spectral region [4–7].

Seeded FEL schemes need precise synchronization of laser and beam. Usually the electron beam duration for FEL is from picosecond down to femtosecond, and pulse length of the seed laser is at the same level. Thus the synchronization precision should be sub-picosecond and sometimes even down to femtosecond level. Such stringent requirement could be fulfilled with various ways, such as high harmonic phase-locked loop (PLL) and optical cross-correlation [8].

FEL experiments of HGHG, echo-enabled harmonic generation (EEHG) [9–11]and cascaded HGHG [12–14] have been carried out, and chirped pulse amplification [15, 16] are underway at Shanghai Deep-Ultraviolet Free-Electron Laser test facility (SDUV-FEL) [17], which is consisting of an injector, a main accelerator, a bunch compressor, two laser modulation stages, and a long undulator section. The seed laser interacts with the electron beam in the two modulator undulators.

All these experiments are externally seeded, and precise synchronization between the seed laser and electron beam is necessary. In this paper, the history and current status of related laser and synchronization systems are reviewed. Some measurement results are also presented.

* work supported by the National Natural Science Foundation of China (Grant No. 11175241)
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LASER SYSTEMS

The SDUV-FEL was originally a SASE test facility, and had only one Nd:YLF laser system serving as the drive laser. With some modification on the laser transport system, it had been successfully turned into a HGHG test facility since 2009. One Ti:Sapphire laser system was put into operation as the dedicated seed laser in 2010 and an optical parametric amplifier (OPA) system was added to extend the capability in 2011. Currently, a rather complicated laser transport system has been established to fulfill different requirements, which is shown in Figure 1.

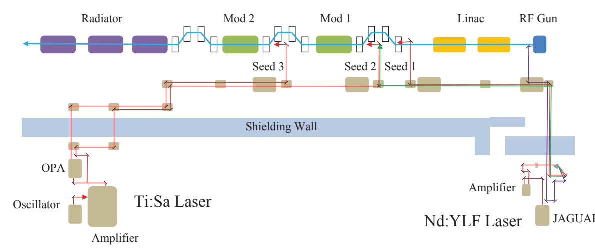

Figure 1: Layout of the laser transport system.

There are three laser injection points and two modulation sections along the beam line. The seed laser could be coming either from the Nd:YLF system or from the Ti:Sa system depending on the requirement of the planned experiment.

Nd:YLF Laser

The basic parameters of the Nd:YLF laser system is shown in Table 1.

Table 1: Parameters of the Nd:YLF Laser System

Parameter	Value	Remark
Wavelength	1047 nm	fundamental
Pulse length	8.7 ps	FWHM
Repetition rate	119 MHz	oscillator
Repetition rate	2 Hz (100 Hz max.)	amplifier
	>5 mJ@1047 nm	amplifier
Pulse energy	>2 mJ@523 nm	2nd harmonic
	>1 mJ@262 nm	4th harmonic

The Nd:YLF laser is mainly used to drive the RF gun at its fourth harmonic through two BBO crystals, while the residual fundamental and second-harmonic light could be used as the seed laser.

ISBN 978-3-95450-133-5

Ti:Sapphire Laser

The basic parameters of the Ti:Sapphire laser system is shown in Table 2.

Table 2: Parameters of the Ti:Sa Laser System

Parameter	Value	Remark
	750 –-860 nm	
Center wavelength	1160 –-1600 nm	OPA signal
	1600 –-2600 nm	OPA idler
Pulse length	35 fs, 130 fs, 1 ps	FWHM
Repetition rate	79.333 MHz	oscillator
Repetition rate	1 kHz	amplifier
	>3.5 mJ@800 nm	amplifier
Pulse energy	>400 μJ	OPA signal
	>300 μJ	OPA idler

The Ti:Sapphire laser system is utilized as a dedicated seed to provide various wavelength output at different pulse length. With the OPA system, the laser seed could be tuned continuously from 1160 nm to 1600 nm or from 1600 nm to 2600 nm, thus we could continuously tune the FEL output without varying the electron beam energy.

SYNCHRONIZATION SYSTEM

Tuning of the Synchronization

At first, the seed laser and the electron beam are adjusted to be transversely overlapped through two frosted YAG screens which are placed upstream and downstream the modulator, respectively.

The longitudinal overlap of the seed laser and the beam is accomplished in two steps. Coarse synchronization is tuned with a PD and an oscilloscope. The beam and the seed laser could be observed by detecting the undulator radiation signal of the electron beam and the seed laser simultaneously by a PD downstream the modulator. By using a 1 GHz PD and a high resolution oscilloscope with 6 GHz bandwidth and 25 GS/s sampling rate, the electron beam and the seed laser could be temporally overlapped with a precision better than 100 ps.

Final precise synchronization is achieved by observing the radiation signals from the radiator while fine tuning the seed laser delay. When the seed laser does not interacts with the electron beam, only the spontaneous emission could be observed in the radiator undulator, which is rather weak. While one adjusts the laser delay with femtosecond level precision to the right direction, the stronger and stronger radiation signal will indicate final synchronization of the seed laser and the electron beam.

After longitudinal position is tuned to be fully coincident, the optimal interaction between the laser and the beam could be found by fine tuning of the transverse position while observing the radiation. Other parameters, such as the modulator gap, chicane strength and the radiator gap, could also be optimized to fulfill the resonant condition, and hence increase the signal to noise ratio.

Original Scheme

The first HGHG experiment on SDUV-FEL is accomplished with a seed laser coming from the drive laser, which is actually the residual fundamental output after the first BBO crystal. The distribution system for the reference signals is shown in Figure 2. The frequency of master RF oscillator is 119 MHz, which is the same as the repetition rate of the drive laser oscillator, while the 2856 MHz reference for low-level RF systems is generated by a multiplier. Path length of the IR laser from the source to the interaction point inside modulator is designed almost equal to that of the UV laser plus electron bunch, and can be finely adjusted remotely by a motorized delay stage.

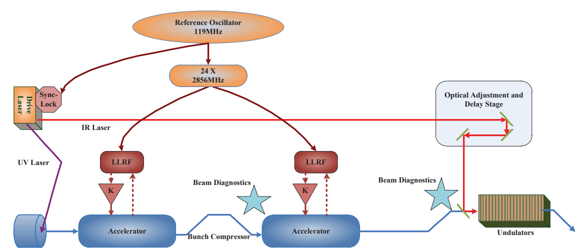

Figure 2: Original reference distribution system for the SDUV-FEL.

The auto-correlation measurement demonstrates that the pulse length of the drive laser is 8.7 ps (full width at half maximum, FWHM). In this experiment, the electron beam is accelerated on crest and the bunch compressor is off. That is to say, the electron beam and the laser will be of the similar length.

The coherent radiation intensity versus the laser delay is shown in figure 3. The FWHM is about 15 ps, which agrees with the laser pulse length measurement result.

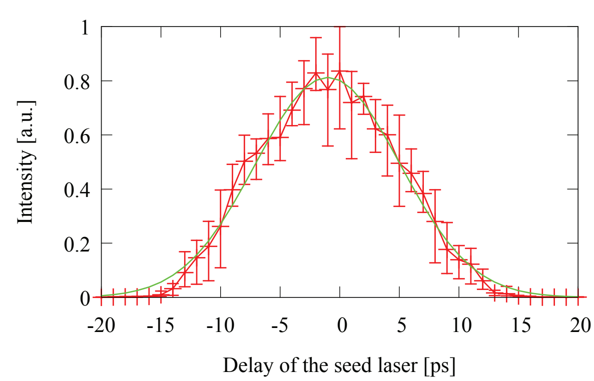

Figure 3: Measurement result of the seed laser scanning.

Current Scheme

In 2010, a Ti:Sapphire system was integrated into the SDUV-FEL to do some more sophisticated experiments.

ISBN 978-3-95450-133-5

The new laser oscillator is working at 79.333 MHz, which is 2/3 of the drive laser. To make the laser pulse synchronized to the electron bunch, the timing and synchronization system must be upgraded to adapt to the changes, which is shown in Figure 4. A new customized master source based on crystal oscillator was built to provide phase-locked 119 MHz and 79.333 MHz references with very low phase noise. A commercial delay generator is used to scale down the reference frequency and provide triggers with different delays.

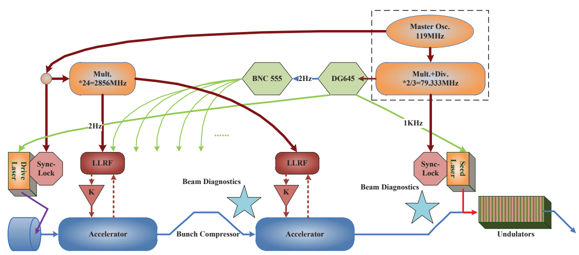

Figure 4: Current synchronization scheme for the SDUV-FEL.

After the new dedicated Ti:Sapphire seed laser is put into use, it's able to measure the beam profile directly. The new seed laser is 130 fs FWHM, and can resolve the bunch profile easily in sub-picosecond level.

Two different cases are demonstrated in Figure 5. One is for the uncompressed bunch (Fig. 5(a)), while the other is for the compressed bunch with the theoretical compression ratio of 2 (Fig. 5(b)). The results agree well with the theory and the simulation. The intensity fluctuations observed are mainly contributed by the beam energy instability and the timing jitter between the seed laser and the beam.

A rough estimation of the timing jitter between the laser and the beam could also be done from the scanning result. From the measurement data, one could estimate that the timing jitter during a short time period is about 1.0 ps. Further optical cross-correlation experiments are considered to verify these estimations.

Direct measurement of the relative phase between the laser and reference signal could also give some information of the synchronization system, as shown in Figure 6. Short time jitter is at sub-picosecond level, however, the drift is rather large. Further measurements are planned in order to determine which part contributes most, the reference distribution or the laser locking box.

Future Plan

For the SDUV-FEL, the bunch length of electron beam is at picosecond level, thus jitter and drift is not a big problem during various FEL experiments. However, for future FEL facilities, especially for user experiments, jitter and drift will be of great concern. Based on the pulsed laser technologies, a high performance synchronization system has been developed [18] to fulfill the requirements for future XFELs. Development of such kind of system is also planned in China and some key technologies will be tested on the SDUV-FEL,

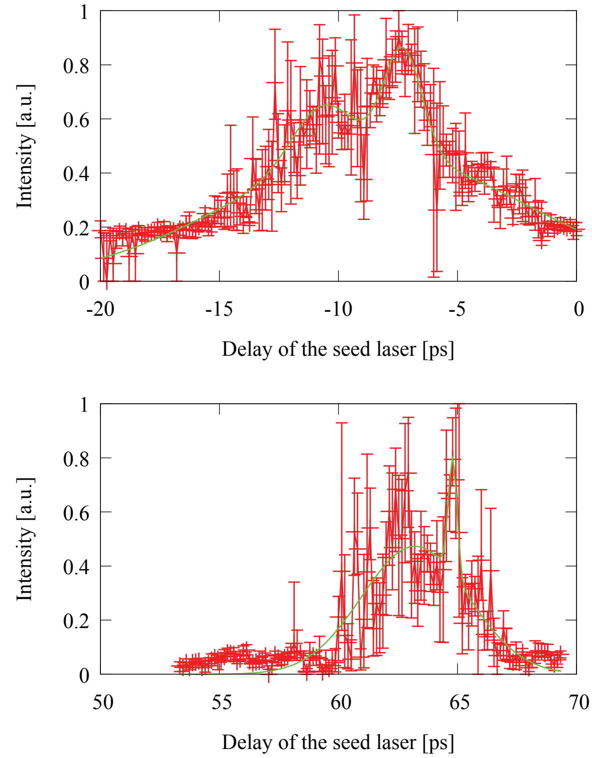

Figure 5: Seed laser delay scan for (a) the uncompressed beam and (b) the compressed beam.

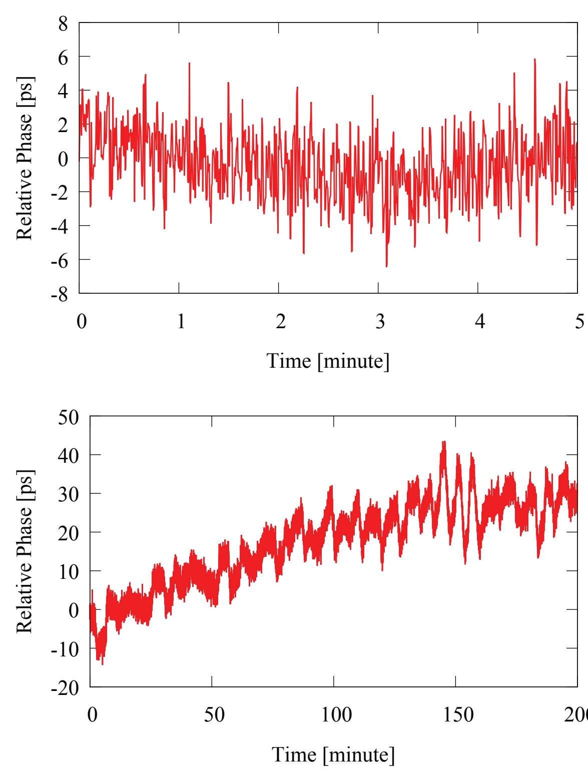

Figure 6: Jitter between the seed laser oscillator and the reference signal for (a) 5 minutes and (b) 200 minutes.

ISBN 978-3-95450-133-5

as shown in Figure 7. An Er-doped fiber laser locked to the RF oscillator will generate femtosecond laser pulses as reference. Through a phase stable fiber distribution subsystem, the reference optical pulses will be sent to different locations along the facility. The drive and seed lasers can be locked to the reference with laser-laser synchronization device which is based on optical cross-correlation, while the low noise RF signals for LLRF systems will be regenerated from the reference with the RF-laser synchronization device based on balanced optical-microwave phase detector. The stable reference can also be used for beam diagnostics directly.

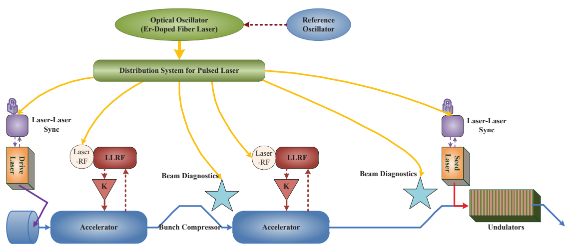

Figure 7: Future upgrade plan for the SDUV-FEL synchronization system.

CONCLUSION

Two solid-state laser systems serving as the drive and seed lasers have operated at SDUV-FEL for a few years. Kinds of seeding schemes are developed to fulfill different requirements of various FEL experiments. The pulse energy has been increased to provide more electron charge and more modulation power through several upgrades. Energy stability and pointing stability are main concerns in the future.

Precise synchronization between the laser and the beam is achieved, which is a necessity for seeded FEL experiments. A general approach is established to make the synchronization process easy and regular. The electron bunch profile is measured with the laser scanning technique, and the results agree with the theoretical expectation and the simulation.

Current synchronization is obtained by RF phase-locked loop, and all reference signals are derived from the same crystal oscillator. However, RF phase-locked loop has some limitations, such as low precision and large long-term drift, which is not a big problem for the long electron bunches and single-stage HGHG operation. But for cascaded HGHG and very short bunches, it requires much more stringent synchronization down to a few femtoseconds. A pulsed laser based optical synchronization system is under consideration for the SDUV-FEL, which will improve the synchronization precision and stability.

ACKNOWLEDGMENT

The authors would like to thank the operation staffs in the Shanghai Institute of Applied Physics for the excellent support during the SDUV-FEL experiments.

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ISBN 978-3-95450-133-5