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# INNOVATIVE IDEAS FOR SINGLE-PASS FELS

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## *Abstract*

SASE FELs (Self-Amplified Spontaneous Emission Free-Electron Lasers) are a powerful light source in short wavelengths from VUV to X-ray regions to investigate matters and phenomena. SASE was first experimentally obtained in 2000 at DESY TTF (Tesla Test Facility) with an output wavelength of 109 nm. Subsequently, FLASH, LCLS and SACLA have achieved lasing in VUV, soft X-rays and hard X-rays. Although SASE has already been widely used for many application experiments in broad scientific fields, its spiky spectrum and time structures due to the lack of longitudinal coherence sometimes become problematic. To improve its longitudinal coherence, various ideas have been proposed and some of them are already experimentally demonstrated, such as a self-seeded scheme, high-gain harmonic generation (HGHG) and echo-enabled harmonic generation (EEHG). There is also another direction of developments to enhance the capability and potentiality of SASE, for example short pulse generation and two-color lasing. This paper reviews recent innovative ideas on single-pass short-wavelength FELs to improve their performance and usability.

## INTRODUCTION

SASE is short for Self-Amplified Spontaneous Emission proposed in 1980's, namely synchrotron radiation from a highly bright electron beam is self-amplified in a single pass through undulators [1, 2]. Since no optical cavity is necessary in the scheme of SASE, it is beneficial for short-wavelength FELs, particularly for X-ray FELs (XFELs).

First experimental proof of SASE was obtained in DESY TTF at the wavelength of 109 nm in 2000 [3]. Then the FLASH facility, which is a successor to TTF and the first user facility of SASE FEL, has extended the wavelength range down to the water window [4]. In hard X-rays, LCLS at SLAC achieved the first lasing at 0.15 nm in 2009 and SACLA at 0.06 nm in 2011 [5, 6]. Nowadays SASE FELs are recognized as a powerful and invaluable tool to investigate ultrafast phenomena with high spatial resolution in diverse scientific fields.

SASE generates transversely coherent light with peak brightness ten orders of magnitude higher than that of conventional synchrotron radiation. However it has inherently poor longitudinal coherence because synchrotron radiation with random phases is amplified without any spectral purifier. The lack of longitudinal coherence results in a noisy spectra and a temporal distribution, which are sometimes harmful to user experiments. Also since a linac (linear accelerator) is used to generate highly bright beam required for SASE, the number of user experiments running at a time is limited.

In order to solve these problems and improve the performance and usability of SASE FELs, numerous innovative ideas have been proposed, and some of them are already experimentally demonstrated and even applied to perform the user experiments. One important direction of the proposed ideas is to mitigate the lack of longitudinal coherence and realize a fully coherent light source. The other direction of the developments aims to improve the performance and usability of SASE.

## LONGITUDINAL COHERENCE

There are several ways to improve the longitudinal coherence of SASE FELs. To improve longitudinal coherence, phase correlation is necessary over the whole length of the electron bunch. The most direct way to achieve this condition is to feed an external coherent seed at the same wavelength as SASE. Then the electron density modulation is printed on the electron bunch at the same phase as the coherent seed, so the emission from the entire electron bunch is aligned in phase. However it becomes difficult to find an external coherent source as being shorter the wavelength. In soft and hard X-rays, monochromatized SASE can be used as a coherent seed instead of an external light source.

Other solution is frequency up-conversion techniques. By using an optical laser, the density modulation is first formed at a longer wavelength, then its frequency is up-converted either by the use of harmonic components or the manipulation of the electron density modulation.

The last approach is to extend the correlation length to the length of a photon pulse by retarding and slipping the electron bunch with respect to the radiation fields in undulators.

### *Seeded FEL*

In UV and VUV spectral regions, high-order harmonic generation (HHG) in gas can be used as an external coherent source [7-10]. The first experiment was demonstrated at the SCSS test facility [11]. Figure 1 is the measured spectra of SASE and a seeded FEL at the wavelength of 160 nm. In the temporal domain, a SASE pulse is composed of many spikes independently emitted and amplified from different longitudinal positions of the electron bunch at random phases. It results in a spiky spectral structure as shown figure 1 (a). In contrast, the spectrum of the seeded FEL has a single peak indicating that the emission from the electron bunch induced by the coherent seed is aligned in phase.

The wavelength of the seeded FEL using HHG has been shortened down to 61 nm at the SCSS test facility and 38 nm at sFLASH [12, 13].

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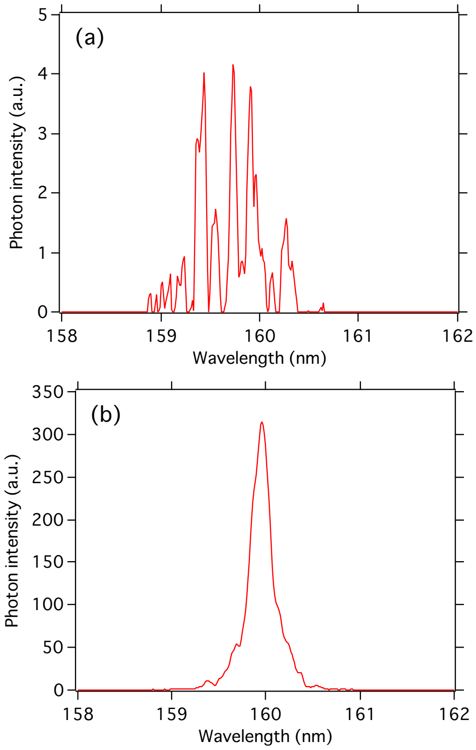

Figure 1: Spectra of (a) SASE and (b) a seeded FEL measured at the SCSS test accelerator for the wavelength of 160 nm [11].

## *Self-seeded FEL*

The extension of direct seeding to soft and hard X-rays confronts insufficient power or absence of a coherent seed source. Instead, by dividing the undulators into two sections and installing a monochromator in between, a self-seeded FEL was proposed at DESY [14]. SASE from the first undulator section is monochromatized and used as a coherent seed for the second section. To set up a monochromator, a chicane is installed to detour the electron beam and adjust the longitudinal overlap between the monochromatized seed pulse and the electron bunch in the second undulator section.

The first experimental demonstration was performed at LCLS in hard X-rays around 8 keV [15]. Instead of a complicated multi-reflection geometry, monochromatized transmission from a single crystal was used, in which coherent wake fields trailing the main transmission pulse were used as a seed [16]. This simple geometry enables to reduce the size of the chicane. The self-seeded XFEL with the same geometry was also tested at SACLA [17].

## *HGHG FEL*

HGHG was first proposed and demonstrated at BNL in infrared wavelengths [18]. Similar to the seeded FEL, the electron bunch is overlapped with a coherent seed in the first undulator section, so-called a modulator, but at a long wavelength. Then the electron energy is modulated at the period of this seed wavelength as shown in figure 2. When the electron beam passes through the chicane located downstream of the modulator, the energy modulation turns into a density modulation with harmonic components. By tuning the second undulator section to one of these harmonic wavelengths, coherent radiation is emitted at the harmonic wavelength of the original seed.

The clear advantage of HGHG is that a coherent seed is necessary only at subharmonic of the target wavelength. The magnitude of this frequency up conversion is limited by harmonic order contained in the electron density modulation, which is mainly determined from the energy spread of the electron beam. To reach VUV or X-rays using a visible laser, the HGHG process should be repeated several times. Currently the most successful user facility using the HGHG scheme is FERMI [19]. They have reached 4 nm using two-stage HGHG together with the bunch technique [20, 21]. The radiation from the first HGHG stage is used as a coherent seed for the second stage and the interaction part of the electron bunch is displaced between the first and second stages.

Recently a new idea comes out to improve the harmonic order and efficiency of HGHG by manipulating the electron beam energy spread [22].

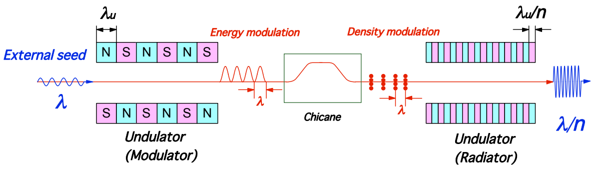

Figure 2: Schematic of a single-stage HGHG configuration.

## *EEHG FEL*

EEHG uses three undulator sections and two chicanes [23]. In the first undulator and chicane, the electron energy is modulated at a long wavelength seed, and it is over compressed in the first chicane. Then a banding pattern with discrete energy gaps appears on the electron distribution in the energy-time phase space. The electron beam energy is modulated again using a long wavelength seed in the second undulator. Finally the energy-modulated banding pattern is compressed in the second chicane and it is transformed into periodical electron density peaks on the time axis. The third undulator section is tuned to the period of the density peaks, then coherent radiation at much shorter wavelength compared to the original coherent seeds can be obtained.

Experimental demonstrations have been performed at NLCTA at SLAC and SDUV-FEL [24-26]. The advantage of EEHG is a relaxed constraint for the harmonic order compared to HGHG, so shorter wavelength could be generated by a single-stage frequency up conversion.

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### *iSASE FEL*

In the undulators, the radiation field advances over the electron beam by one radiation wavelength at each undulator period, which is called slippage. The slippage length over the whole undulator length is generally much smaller than the electron bunch length, so the radiation field can interact with only a limited part of the electron bunch. Many of such local independent interactions occur on the electron bunch resulting in a spiky temporal structure of SASE. So if the slippage length can be extended to the length of the electron bunch, phase correlation and longitudinal coherence can be established over the entire electron bunch, which is an analogy to an optical cavity. This idea is called iSASE (improved SASE) or HB-SASE (High-Brightness SASE) and it was demonstrated at LCLS [27, 28]. In the demonstration, the undulators were alternately detuned except for the first several undulators used to establish SASE. The detuned undulators worked as an electron beam retarder. The experimental results show narrower and smoother spectrum compared to that of SASE indicating better longitudinal coherence of iSASE FEL.

## FOR BETTER PERFORMANCE AND USABILITY OF SASE

Compared to storage ring based synchrotron radiation sources, SASE generates femtoseconds high peak intensity photon pulses. These features are suited for the dynamical study of ultrafast phenomena. For the investigation of ultrafast processes, a pump-probe technique, in which two photon pulses are generated by FEL and a synchronized optical laser, has been widely used. But in order to go to even shorter time scales of attoseconds, the photon pulses of the same time scale are required. The generation of multi-color photon pulses from FEL is also an attractive scheme, since it can eliminate the temporal jitter between the pump and probe pulses. From these reasons, the short pulse generation and multi-color operation are actively explored.

From the viewpoint of usability, the SASE facility is in principle a single-user facility, but quasi-parallel operation of plural beamlines can improve the efficiency of the user operation. In the multi-beamline operation of SASE, the electron beam is distributed to each beamline from bunch to bunch, and the beam energy of each electron bunch should be optimized to the photon wavelength required for each beamline. One idea to realize multi-energy acceleration of a linac is introduced.

### *Short Pulse Generation*

Small-charge short-bunch operation and highly compressed bunch operation are traditional ways to generate short photon pulses [29]. They have routinely provided a few fs pulses to the user experiments at LCLS and SACLA [30]

Another way to shorten the photon pulse length is the use of a slotted foil inserted in an energy dispersive location of an accelerator. If the electron bunch has an energy chirp, its transverse and longitudinal positions are correlated on the foil. The emittance of the electrons hitting to the foil is spoiled due to Coulomb scattering, while that of the electrons passing through the slot is maintained. As a result, SASE is emitted only from an unspoiled part of the electron bunch and a short photon pulse can be obtained. By changing the shape of the slot, the number and location of the emission part on the electron bunch can be controlled. The slotted foil method was proposed and demonstrated at LCLS [31, 32]. This method has also been used for various purposes, not only for the short pulse generation but also for two-color operation and other schemes [33, 34].

Although the pulse length of SASE has not reached attoseconds yet, many ideas have been proposed and examined by numerical simulations [34-43].

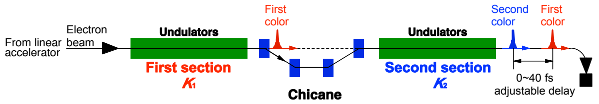

Figure 3: Configuration of the undulators for two-color operation.

### *Two- or Multi-color FEL*

Two-color FEL has a long history since 1994 when the first two-color FEL was achieved at the CLIO infrared cavity type FEL [44]. After more than ten years, FERMI demonstrated the first two-color HGHG operation in VUV [45, 46], and LCLS achieved the first two-color SASE operation in soft X-rays and SACLA in hard X-rays [33, 47].

In the two-color operation of SASE, the undulators are divided into two sections and the magnetic fields (K values) of each section are set at different values. Figure 3 is a configuration of the SACLA undulators for two-color operation. Two photon pulses emitted from the first and second sections have different wavelengths. By installing a chicane between the two sections, the temporal separation or delay between the two photon pulses can be controlled at sub-femtosecond resolution. Both wavelengths are independently tunable and the separation of them can be extended to more than 30 % by using variable-gap undulators.

One disadvantage of two-color operation is decrease of pulse intensity compared to that of single-color operation. Since two-color pulses are both emitted from the same electron bunch, the increase of the electron beam energy spread in the first section affects the SASE gain of the second section. So two-color pulses can not reach the saturation level of single-color operation.

To overcome this limit, two electron bunches generated from a photo-cathode electron gun were accelerated to different beam energies at LCLS. In this case, the two-color pulses do not share the electron bunch, so these pulses can reach the same saturation level as single-color operation at both wavelengths. Further sophisticated schemes of multi-color operation and two-color self-seeded operation using plural Bragg diffraction lines are also recently tested at LCLS [48, 49].

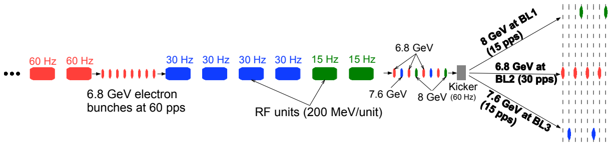

Figure 4: Linac setup for multi-energy operation.

### *Multi-energy Operation*

So far all XFEL facilities in operation have only one beamline. But to meet the growing number of user experiments, multi-beamline operation is highly requested in all facilities. Depending on the photon energies used for the experiments, the optimum electron beam energy differs from one beamline to the other. To achieve the operation of plural beamlines in parallel, the electron beam energy should be controlled from bunch to bunch. The multi-energy operation of a linac was first proposed at SACLA to provide the optimum energy electron bunches to each beamline [50]. In this operation, the number of accelerating structures are changed from bunch to bunch by controlling the repetition frequency of the RF power sources. Figure 4 is an example of the configuration. This operation has been successfully demonstrated at SACLA. Combining with an electron bunch distribution system using a kicker magnet, this multi-energy operation will ameliorate the usability and efficiency of the XFEL facility.

## SUMMARY

So many innovative and unique ideas have been proposed to improve the performance of single-pass short-wavelength FELs. Some of them have been already experimentally demonstrated and they have made a breakthrough in the performance of SASE. In addition to the ideas shown in the paper, there are also many other ideas of a mode-locked FEL [51], pSASE (Purified SASE) [52] and an X-ray cavity [53] to improve the longitudinal coherence, harmonic lasing [54, 55] to extend the photon energy range. Of course the combination of these ideas could produce even better performance and characteristics.

The short wavelength FEL has already established its position as a powerful and useful light source. So it is important that the implementation of new ideas should aim at the benefits of the users. Novel ideas mostly require ultimate stability of the accelerator. Therefore the progress of the accelerator technology is also a key issue for the future FELs.

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