Self-Amplification of Coherent Energy Modulation in Seeded Free-Electron Lasers

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The spectroscopic techniques for time-resolved fine analysis of matter require coherent X-ray radiation with femtosecond duration and high average brightness. Seeded free-electron lasers (FELs), which use the frequency up-conversion of an external seed laser to improve temporal coherence, are ideal for providing fully coherent soft X-ray pulses. However, it is difficult to operate seeded FELs at a high repetition rate due to the limitations of present state-of-the-art laser systems. Here, we report the novel self-modulation method for enhancing laser-induced energy modulation, thereby significantly reducing the requirement of an external laser system. Driven by this scheme, we experimentally realize high harmonic generation in a seeded FEL using an unprecedentedly small energy modulation. An electron beam with a laser-induced energy modulation as small as 1.8 times the slice energy spread is used for lasing at the 7th harmonic of a 266-nm seed laser in a single-stage high-gain harmonic generation (HGHG) setup and the 30th harmonic of the seed laser in a two-stage HGHG setup. The results mark a major step towards a high-repetition-rate, fully coherent X-ray FEL.

X-ray free-electron lasers (FELs) that provide high-brightness pulses of femtosecond duration and tunable wavelengths have enabled new research in various scientific fields.\textsuperscript{[1,2]} To date, most successful FEL-based experiments have investigated the internal structure or ordering of materials, which is compatible with single-pulse detection\textsuperscript{[3]}. In contrast, spectroscopic probes used to study magnetic and electronic structures require a higher average photon flux on the sample. Therefore, coherent radiation with a high repetition rate provided by the FEL is required for high-resolution spectroscopy experiments.

Most X-ray FEL facilities worldwide\textsuperscript{[4–7]} employ the mechanism of self-amplified spontaneous emission (SASE)\textsuperscript{[8]}. The SASE scheme can obtain FEL pulses with sub-angstrom wavelengths but limited temporal coherence, as the initial amplification arises from the electron-beam shot noise. The phase and intensity fluctuations of the SASE scheme severely limit the use of X-ray spectroscopy. Self-seeding schemes\textsuperscript{[9,10]} can be used to achieve narrow-bandwidth pulses but at the cost of shot-to-shot intensity fluctuations. Seeded FELs\textsuperscript{[11–13]} triggered by stable, coherent external lasers ensure output FEL pulses with a high degree of temporal coherence and small pulse energy fluctuation, as has been demonstrated by analytical calculations and experimental results in the ultraviolet to soft X-ray range\textsuperscript{[14,20]}.

In recent years, based on the superconducting linac, the XFELs with repetition rates of up to several MHz have been proposed\textsuperscript{[21,22]}. A seeded FEL with such a high repetition rate can meet the requirements of high-resolution spectroscopic techniques for fine analysis of the matter. Meanwhile, borrowing the idea from seeded FELs, most storage-ring-based FELs employ external lasers to manipulate electron beams to precisely tailor the properties of the radiation pulses\textsuperscript{[23,24]}. However, owing to the limitations of present state-of-the-art laser systems, the repetition rate of an external seed laser with sufficient power to manipulate the electron beam is limited to the kilohertz range. There is a continuing trend towards higher repetition rates for future XFEL facilities and scientific requirements.

Various methods to realize a high-repetition-rate seed source are under investigation. The concept of employing an FEL oscillator as the seeding source for subsequent cascades is proposed\textsuperscript{[26–28]}, which requires further experimental validation. Recently, an optical, resonator-like seed recirculation feedback system is introduced to recirculate the radiation in the modulator to seed the following electron bunches\textsuperscript{[29]}. Since the critical limit to the repetition rate of a laser system is the thermal effect of the optics, reducing the peak power can effectively increase the repetition rate. In this Letter, we report the use of self-amplification of coherent energy modulation in a seeded FEL to relax the power requirement of an external seed laser by more than an order of magnitude.

The setup of the self-amplification scheme is displayed in Fig.\textsuperscript{[1]}. This setup is similar to the pre-density modulation scheme\textsuperscript{[31,32]} proposed to enhance the microbunching and reduce the energy spread. Compared to the single-stage high-gain harmonic generation (HGHG)\textsuperscript{[11]}, an additional chicane and another short undulator are added after the modulator in the self-amplification scheme. The electron beam interacts with an external laser in the modulator and is induced with an energy modulation equal to or twice the slice energy spread. The first chicane in this scheme is used for density modulation.
of the electron beam. Because the required energy mod-
ulation amplitude for amplification at the \(n\)th harmonic
should be \(n\)-fold larger than the slice energy spread in
the HGHG scheme, an electron beam with such a small
energy modulation amplitude is difficult to be used for
lasing at high harmonics. However, it can be used to
produce strong radiation at the fundamental wavelength.

Since the intensity of the coherent radiation generated
by a microbunched beam is strongly coupled with the
bunching factor and transverse size of the electron beam
[33], the energy modulation enhancement can be con-
trolled by the chicane before the self-modulator or the
transverse focusing. As indicated by the phase spaces
of the electron beam in Fig. 1, the initial energy mod-
ulation introduced by a low-peak-power seed laser can
be greatly amplified through the self-modulation under a
reasonable electron-beam envelope. Based on the ampli-
fied energy modulation, various seeded FEL schemes can
be combined following the self-modulator. As presented
in Fig. 1, a second chicane and a radiator after the self-
modulator, used to achieve a large bunching factor and
lasing at high harmonics, make it a typical HGHG layout.

A proof-of-principle experiment was conducted at the
Shanghai Soft X-ray FEL Test Facility (SXFEL) [34]
to demonstrate the self-amplification of coherent energy
modulation. The first stage of the SXFEL has the same
setup presented in Fig. 1, which comprises a seed laser
with a wavelength of 266 nm and a pulse length of 160 fs
(FWHM), two modulators of length 1.5 m and period 80
mm, and two magnetic chicanes. The second modulator
is treated as the self-modulator in the experiment. Con-
ected to the second chicane, four undulator segments of
length 3 m and period 40 mm are adopted as the radiator
of the first stage.

In the experiment, we first employed the coherent ra-
diation based method [35] to measure the laser-induced
energy modulation. In the measurement, the seed laser
with three different pulse energies of 38.10, 6.10, and 1.56
\(\mu\)J was used to interact with the electron beam with an
energy of 795 MeV and a bunch charge of 550 pC in the
modulator, respectively. The modulated electron beam
was used to generate coherent radiation at the funda-
mental wavelength in the self-modulator. The first chi-
cane was scanned to determine the optimal dispersion
strength that maximizes the coherent radiation intensity
under different pulse energies of the seed laser. For each
optimal dispersion strength, a numerical relationship be-
tween average slice energy spread and energy modulation

![FIG. 1. The self-modulation scheme together with the electron-beam longitudinal phase spaces at various positions. The electron beam is imprinted onto a small energy modulation with an amplitude of \(\Delta E = \sigma_E\), where \(\sigma_E\) represents uncorrelated energy spread, by a seed laser with a wavelength of \(\lambda\) in the modulator. After that, the electron beam passes through the first chicane for density modulation. In the following self-modulator, the energy modulation amplitude is enhanced tenfold by the self-modulation under an average electron-beam envelope of 100 \(\mu\)m. The numerical simulation is performed by GENESIS1.3 [30].](image1)

![FIG. 2. Relationship between the energy modulation amplitude induced by a 1.56 \(\mu\)J seed laser and the initial slice energy spread.](image2)
amplitude can be obtained. The obtained optimal $R_{56}$ of the first chicane under the three pulse energies were 0.17, 0.38, 0.63 mm, respectively. Fig. 2 shows the three numerical curves obtained from the three optimal dispersion strength, where all the energy modulation amplitudes are scaled down to the amplitude induced by a 1.56 $\mu$J seed laser. The intersection of any two curves is a solution for the measurement. Thus, three solutions were obtained and the average of them was treated as the final measurement result. The measured slice energy spread and energy modulation amplitude induced by the seed laser of 1.56 $\mu$J are 40 and 73 keV, respectively. The energy modulation amplitude is approximately 1.8 times the slice energy spread. The pulse energy of 1.56 $\mu$J was used in the following experiments to verify the feasibility of the self-amplification scheme.

We further performed the self-modulation and demonstrated the amplification of the laser-induced energy modulation. Since the self-modulation also utilizes the strong coherent radiation produced in the self-modulator, the $R_{56}$ of the first chicane was set at the optimal value of 0.63 mm obtained in the previous measurements. To verify the energy modulation enhancement, the electron beam was sent to the radiator for lasing at high harmonics, where only one undulator segment was used. The undulator segment gap was scanned continuously from 9.2 to 18 mm, which contained resonances at the 4th to 10th harmonics of the external laser. When the self-modulator was removed, no coherent radiation was detected by the photodiode after the radiator. Subsequently, the resonance of the self-modulator was tuned to the fundamental wavelength of the seed laser. In this case, coherent radiation can be detected even when the radiator is resonant at the 9th harmonic. The result proves the enhancement of the initial energy modulation. Fig. 3 (a) displays the coherent radiation intensity at various harmonics when the $R_{56}$ of the second chicane is set to 0.16 mm, which was not precisely optimized for a specific wavelength.

Because intense radiation can be detected at the 7th harmonic of the seed laser, i.e., 38 nm, we carefully optimized the dispersion strength of the second chicane at this wavelength. The optimal $R_{56}$ of the second chicane for the 7th harmonic is 0.17 mm. As the energy modulation is not directly induced by the external laser, it is difficult to measure the enhanced energy modulation amplitude using the coherent radiation based method. To roughly evaluate the energy modulation amplitude, we can consider that the enhanced energy modulation is induced by a strong seed laser and the initial slice energy spread of the electron beam is the previously measured 40 keV. According to the relationship between the optimal dispersion strength and the energy modulation amplitude, the energy modulation amplitude after the self-modulation can be estimated as 218 keV. This means that the energy modulation amplitude was increased approximately threefold.

To verify the capability of the self-modulation scheme for FEL lasing, the other undulator segments of the radiator are used to further amplify the coherent radiation. The resonance condition of the radiator is maintained at the 7th harmonic of the seed laser. This is the first time that the first stage of the SXFEL operates at the 7th harmonic. The measured gain curve along the radiator and one typical transverse distribution of the laser pulse are shown in Fig. 4 (b). At the exit of the radiator, FEL pulses with a mean energy of 17 $\mu$J and an rms energy jitter of 5 $\mu$J are obtained. The maximum pulse energy can reach 27 $\mu$J. Fig. 4 (a,b) presents two

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**FIG. 4.** Performance of the FEL lasing at 38 nm. The measured single-shot longitudinal phase space of the electron beam with the seed laser (a) turned off and (b) turned on. (c) Reconstructed FEL pulse temporal profile from the energy loss. Beam head is to left in these plots. (d) 60 consecutive single-shot spectra.
We further explored the feasibility of obtaining shorter wavelengths based on the amplified energy modulation in the cascaded HGHG scheme. The normal operation for SXFEL is a 6 × 5 cascading HGHG setup. Thus, in the experiment, we first changed the resonance of the radiator of the first stage from the 7th to the 6th harmonic by tuning the undulator gap and kept other parameters unchanged. Intense FEL radiation with a central wavelength of 44.33 nm was detected immediately. The measured FWHM bandwidth is 5 × 10^{-3}. The measured FWHM of the 60 shots is 2 × 10^{-3}, which is mainly limited by the resolution of 0.05 nm of the spectrometer.

In addition to conventional laser systems, high harmonic generation in gases (HHG) is a promising extreme ultraviolet seed source for seeded FELs, but with low intensity [35–40]. Using the self-modulation to amplify the energy modulation induced by an HHG source would be a promising option for further frequency up-conversion [41]. Therefore, the results presented here open up many possibilities for future seeded FELs.

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