# PROPOSAL FOR THE GENERATION OF TERAWATT, ATTOSECOND X-RAY PULSES IN FREE ELECTRON LASERS

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*Abstract*

A feasible novel method is proposed to generate attosecond terawatt x-ray radiation pulses in the free-electron lasers, which could find its application on multiple science. In our scheme, a chirped laser is employed to generate a gradually-varied spacing current enhancement and a series of spatiotemporal shifters are applied between the undulator sections to generate ultra-short radiation pulse. Three-dimensional start-to-end simulations have been carried out and the calculation results show that a 0.15-nm x-ray pulse with the peak power of about 1.7 TW and the pulse length of 0.1 fs could be achieved in our scheme.

## INTRODUCTION

X-ray free electron lasers (XFELs) [1] with ultra-short pulse and high power energy would enable observation at the atomic level, providing an ideal tool in various subjects such as biology, material science, physics and chemistry. To date, many developed countries have constructed the x-ray FEL facilities [2-6] and at the same time, more FEL facilities are under-constructing. Nowadays, most of the existing and the under-constructing x-ray FEL facilities take advantage of the self-amplified spontaneous emission (SASE) scheme [7, 8], which can provide good spatial coherence but limited temporal coherence due to its starting from the shot noise. The typical output radiation of the hard x-ray FEL facilities have the central wavelength of 0.1 nm, the peak power at GW level and the pulse duration of about 100 femtoseconds. In order to further improve the performance of the x-ray FEL facilities, especially enhance the peak power and shorten the pulse duration, several new schemes have been proposed and developed in the last decade, trying to increase the resolution of x-ray diffraction imaging experiments.

In order to shorten the output radiation, a conceptually simple method is using low charge electron beam to reduce the electron beam length as well as the radiation pulse length [9,10]. Alternately, one can use the emittacne spoiler technique to spoil most of the electron beam, leaving only a small unspoiled part to lase by employing a slotted foil in the central of the bunch compressor chicane [11]. Similarly, the enhanced SASE (ESASE) takes advantage of an external few-cycle laser to modulate the electron beam in the longitudinal phase space, enhancing the peak current in a short slice for generating attoseconds radiations [12]. However, none of these scheme hold the ability to enhance the output peak power beyond saturation and pulse length of the radiation are limited by the FEL slippage.

Recently, T. Tanaka proposed a scheme that could generate a multi-terawatt, attosecond x-ray pulse, in which an eSASE section is required consisting of an undulator module, a dispersion section and an X-ray delay system [13]. However, it is quite challenging to delay the hard X-ray in the vacuum. Later on, E. Prat proposed a simple method to generate terawatt-attosecond X-ray FEL pulses by utilizing the emittance spoiler technique, which is initially proposed for the generation of the ultra-short X-ray radiation [14]. The pulse length of the generating bunch train is about several femtoseconds and it will be very challenging to generate sub-femtosecond pulses, limited by the slice energy spread, the transverse beam size and the coupling between the longitudinal and the transverse.

In this paper, we propose a novel and feasible scheme to generate isolated terawatt x-ray pulses with pulse durations of several tens of attoseconds based on the ESASE scheme and the super-radiant principles. The scheme is quite simper and easily to be applied to the existing and future x-ray FEL facilities as there are no x-ray delay section in the scheme. When compared with the emittance spoiler technique, the proposed technique holds the ability of achieving shorter output pulse durations and has the additional advantage of natural synchronization to external lasers, which is especially important for pump-probe experiments.

## PRINCIPLES

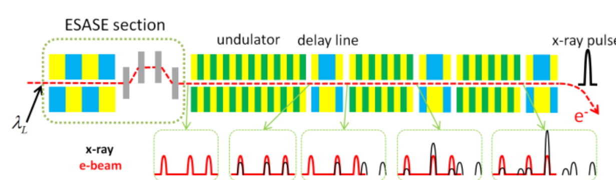


Figure 1: Schematic layout of the proposed technique.

The schematic layout of the proposed technique is illustrated in Fig. 1, consisting of an ESASE section upstream of the undulator and some delay lines inserted among the undulator sections. In the conventional ESASE scheme, an ultra-short laser pulse with no more than two optical cycles is employed to interact with the electron beam in a single period wiggler to introduce an energy modulation. In the proposed scheme, instead of a few-cycle laser pulse, a frequency chirped laser is utilized to imprint a gradually-varied spacing current enhancement

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on the electron beam. This powerful laser pulse with significant and adjustable frequency chirp can be easily obtained by tuning the parameters of the compressor of CPA. The dispersion in the laser pulse does not need to be fully compensated, which would significantly simplify the laser system design for the ESASE scheme. After the density modulation, the electron beam is sent into a long undulator with a series of spatiotemporal shifters between the undulators to amplify a chosen ultra-short radiation pulse via superradiant gain process. In the first undulator section, the gradually-varied spacing current enhancement leads to an uneven spacing radiation pulse train. The first undulator should be relatively long to amplify the target radiation pulse with peak power that is high enough to suppress the shot noise in the following undulator section but still far from saturation to prevent degradation of the electron beam quality. The target radiation pulse is then shifted forward to the following current peak by the delay line while the other radiation pulses are shifted to the low-current part of the beam. The microbunching formed in the current peaks are smeared out by the delay line, preventing the continuous growth of noisy spikes in the following undulators. The target radiation pulse reseeds the fresh peak in the following undulator section, leading to a continuing amplification of the radiation pulse. Repeating this process in the following undulator sections, the target ultra-short pulse can be finally amplified to TW level.

## SIMULATIONS

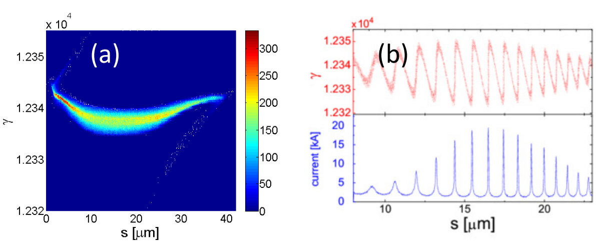


Figure 2: (a) Longitudinal phase space at the end of the linac. (b) Longitudinal phase space and the corresponding current distribution at the end of the ESASE section.

To illustrate the physical mechanism and a possible application with realistic parameters, three-dimensional start-to-end simulations have been performed for the proposed technique. We take the layout and nominal parameters of the Shanghai hard x-ray FEL facility (HXFEL) [15], which is aiming at generating GW-level femtosecond radiation pulse based on SASE. The linac of the HXFEL consists of an S-band photoinjector, a laser heater system, an X-band linearizer, two bunch compressors and three C-band main accelerator sections. At the exit of the linac, the electron beam can be accelerated to about 6.3 GeV with the charge of 250 pC and peak current of 3kA.ASTRA [16] and ELEGANT [17] were used for the simulations in the photoinjector and the remainder of the linac, respectively. The longitudinal phase space of the electron beam at the end of the linac is shown in Fig. 2(a), where one can find that a constant profile of beam energy, energy spread and emittance is maintained in an approximately 50 fs region in longitudinal. In this region, the normalized transverse emittances are around 0.4 mm-mrad in both horizontal and vertical directions and the slice energy spread is about 600 keV. Simulations for the modulation process of ESASE was done with a three-dimensional algorithm based on the fundamentals of electrodynamics when considering the appearance of electric and magnet fields of an chirped laser beam. The FEL gain processes was simulated by GENESIS [18]. A chirped laser pulse with the central wavelength of 800nm, peak power of about 80 GW, beam waist of 200 μ m and pulse length of 40fs (FWHM) is injected to the ESASE modulator (a single period wiggler with period length of 20 cm). The bandwidth of the laser pulse is about 34%, equivalent to a 3.5 fs transform-limit pulse after fully pulse compression.

The longitudinal phase space and current distributions of the electron beam at the exit of the ESASE section are shown in Fig. 2(b), where a gradually-varied spacing current enhancement is achieved with the peak current of about 20kA. The energy modulation amplitude induced by the laser pulse is about 10 times of the initial beam energy spread. Duration of the current spikes in the vicinity of beam center is on the scale of ~100 asec. This electron beam is then sent into the following undulator sections to generate ultra-short radiation pulses at 1.5 Å. The simulation results for the x-ray radiation profile evolution in the undulator are illustrated in Fig. 3.

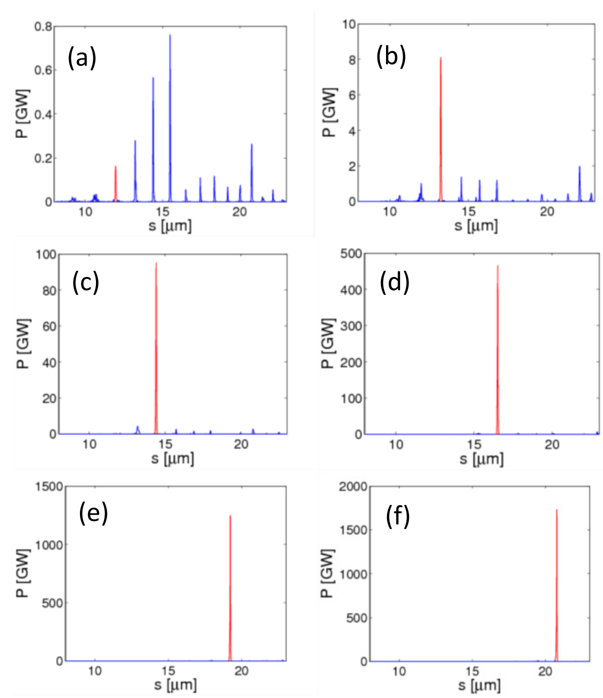


Figure 3: XFEL radiation structure evolutions along the undulator beamline at the end of (a) the 1$^{st}$; (b) the 2$^{nd}$; (c) the 3$^{rd}$; (d) the 5$^{th}$; (e) the 8$^{th}$and (f)the 10$^{th}$ undulator section.

The length of each undulator segment is about 2 m (100 periods) with period length of 18mm. The undulator segments in the 1st to 10th undulator sections are chosen to be 7, 4, 3, 2, 2, 2, 2, 2, 2, 2 to optimize the FEL power and improve the contrast of the target pulse against others. The first undulator section with 7 segments was used to produce an attosecond pulse train with hundred-megawatt-level peak power. The longitudinal profile of the radiation reflects the comblike structure of the current distribution, as shown in Fig. 3(a). After that, delay lines are applied to selectively amplify the target pulse (indicated in red) in the following undulator segments. The delay distances induced by these delay lines should be also gradually-varied to exactly match the interspacings between the current peaks. In order to realize this in a real machine, one needs to measure the frequency distribution of the chirped laser by using optical techniques, providing a reference for setting the strengths of the delay sections. And then one should scan the strengths of these delay sections separately to optimize the final output intensity.

In the second undulator section, the target radiation pulse was shifted forward and overlapped with the next current peak, leading to a continually power amplification and pulse shortening due to the superradiant behavior of ultra-short radiation pulses. Beside the target radiation pulse, we found in the simulations that there are still some degree of overlap between other radiation pulses and current peaks due to the relatively long radiation pulse length (long slippage length) generated from the first undulator section. This results in the appearance of several satellite pulses in addition to the target pulse, as shown in Fig. 3(b). However, the amplification of these satellite pulses does not proceed as the slippage length becomes shorter and shorter in the following undulator sections. As shown in Fig. 3(d), after 5 undulator sections, the peak power of the target radiation pulse is enhanced to about 500 GW, which is already two orders of magnitude higher than that of the satellite pulses. The contrast, which is defined by the percentage of the energy contained in the target pulse, is further improved in the following undulators. After 10 undulator sections, an isolated radiation pulse with pulse length of about 80 asec (FWHM) and the peak power of about 1.7 TW is produced, as shown in Fig. 3(f), while the other (mainly "satellite") pulses are still at a few GW level. The contrast of the target radiation pulse is over 96%. The final output power can be further increased by utilizing more undulator sections and more current spikes. It is worth to point out that the GW-level "satellite" pulses in the final output may still cause potential difficulty on the user experiments and applications in the future.

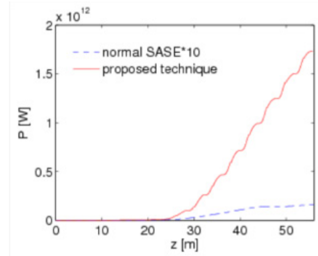


Figure 4: FELpeak power gain curves for normal SASE (blue dashed line) and the proposed scheme (red solid line).

Figure 4 shows the FEL peak power growths along the undulator distance. For comparison purpose, simulations were also performed for the normal SASE case (blue line) with the same electron beam from linac and same undulators but without delay lines. The normal SASE-FEL gets saturation at around 45 m of the undulator with the saturation power of about 13 GW. According to the basic theory of high-gain FEL, the saturation power is proportional to $I_e^{4/3}$, where $I_e$ is the peak current [19, 20]. In the proposed scheme, the peak current has been enhanced by over 6 times (from 3 kA to about 20kA) through ESASE, leading to about 10 times enhancement of the saturation power in each undulator section. In addition, about 10 pulses are compressed to a single radiation pulse. Thus the final output peak power is about two orders of magnitudes higher (red line) than the normal SASE. From Fig. 4, one can also find that the peak power for the proposed scheme growth quadratically with the undulator length in each undulation section after the third undulator section. The strong seed generated from previous undulators initiates this superradiant process, which helps the ultra-short radiation pulse quickly extract energy from the electron beam in a relatively short undulator section.

## CONCLUSIONS

In this paper, we have presented a novel and easy-to-implement method to generate isolated terawatt attosecond x-ray radiation pulses by combining the ESASE section and the mode-locking undulator module. Three-dimensional start-to-end simulation results show that 0.15 nm x-ray radiation pulses with the peak power of about 1.7 TW and the pulse duration of about 80 as could be generated by using the proposed technique. One can further enhance the output peak power and shorten the pulse duration by using a longer chirped laser, more undulator sections and better beam parameters.




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