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Generation of double pulses at the Shanghai soft X-ray free electron laser facility

Zhen Wang[1,2,3] · Chao Feng[1,2] · Qiang Gu[1,2] · Li-Hua Yu[4] · Zhen-Tang Zhao[1,2,3]

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Abstract In this article, we present the promise of a new method generating double electron pulses in picosecond-scale pulse length and tunable interpulse spacing at several picoseconds. This has witnessed an impressive potential of application in pump–probe techniques, two-color X-ray free electron laser, high-gradient witness bunch acceleration in a plasma, etc. Three-dimensional simulations are carried out to analyze the dynamic of the electron beam in a linear accelerator. Comparisons are made between the new method and existing ways.

Keywords Free electron laser · Double pulses · SXFEL

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✉ Zhen Wang
wangzhen@sinap.ac.cn

✉ Zhen-Tang Zhao
zhaozhentang@sinap.ac.cn

1 Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China

2 Shanghai Sciences Research Center, Chinese Academy of Sciences, Shanghai 201204, China

3 Graduate University of Chinese Academy of Sciences, Beijing 100049, China

4 National Synchrotron Light Source, Brookhaven National Laboratory, Upton, NY 11973, USA

1 Introduction

Free electron laser (FEL) [1], recognized as the candidate of generating ultraviolet (UV) and X-rays, has been an impressive development and application worldwide for the past several years. Nowadays, most short-wavelength FEL facilities, such as FLASH in Germany [2], LCLS in USA [3], SACLA in Japan [4] based on the self-amplified spontaneous emission (SASE) scheme [5, 6] and FERMI@Elettra [7, 8] in Italy based on the high-gain harmonic generation (HGHG) process [9–11], show great success to provide coherent, stable and high-intensity XFELs. The growing user demands lead to the continuing improvement of the facility capabilities, such as two-color FEL scheme based on double electron pulses [12, 13], mode-locked FEL scheme based on ultra-fast microbunching pulse trains [14–17].

Applications of two-color radiation [18–20] exist over a broad range of wavelengths involving pump–probe technology. It is common that in the optical regime the use of two-color excitations is often needed. This scheme requires double pulses generated in a linear accelerator with one traveling front and the other following. After being generated in the RF gun and accelerated in the linac, the double pulses are sent to the undulator to generate XFELs in different wavelengths. Besides generating two-color XFELs, double-pulse scheme can also find its applications in the beam-driven plasma acceleration [21, 22], to provide ultra-high accelerating gradient (>GeV/m).

There are two existing methods that are quite suitable for generation of double pulses. One is the emittance spoiler technique, which is initially proposed for generation of ultra-short X-rays [23]. A double-slot foil is inserted into the middle of the chicane (between the second and third dipoles), aimed at spoiling the emittance of most of the electron beams hitting the foil, leaving only two unspoiled parts of the electron. The pulse length and separation of the double pulses can be varied by tuning the slot width and the separation on the foil. Another method is to generate double pulses in the photocathode RF gun and accelerate the double pulses together in the linac [13, 24]. Suffering from a strong longitudinal wakefield, the double electron pulses are over compressed in the bunch compressor chicane to achieve high enough peak currents.

However, in the two methods, the pulse length and the separation of double pulses are limited to several-hundred femtoseconds under the requirement of high peak current with the charge of sub-hundred pC in each pulse. In this paper, we propose a new method to generate double pulses with picosecond-scale pulse length and separation. The double pulses are generated in two adjacent RF buckets in the photocathode gun and then delayed into the same bucket in the first nested chicane. This scheme can provide high peak current and long pulse length with tunable picosecond-scale separation.

The paper is organized as follows. The nested chicane used to delay the front beam to the following RF bucket is described in Sect. 2. In Sect. 3, we show the simulation results using the nested chicane at the Shanghai soft X-ray free electron laser facility (SXFEL). Summaries and conclusions are given in Sect. 4.

2 The nested chicane for time delay

In order to achieve picosecond-scale double pulses, one can generate the double pulses in two adjacent RF buckets. The separation of the double pulses is 350 ps (one frequency period of S-band), ensuring that both pulses meet the same accelerating phase in the injector. In order to delay the first pulse to the following RF bucket, the pulse should pass through a larger chicane. The delay time of the pulse in the chicane is given as $\Delta t = R_{56}/(2c)$, where R_{56} is strength of the chicane and c is the speed of light. So, a 210-mm R_{56} is needed to delay the front pulse to the following RF bucket (about 350 ps).

To achieve this goal, an L-band is inserted upstream of the first chicane, aimed at introducing the energy separation between the double pulses. A nested chicane is designed, as shown in Fig. 1, to delay the double pulses to the same RF bucket. When the double pulses pass through the L-band, the front pulse will lose energy, while the back one will achieve energy. The front pulse with lower energy travels through a large chicane (the red one with large R_{56}) and is delayed to the following RF bucket. The following pulse with higher energy passes through a small chicane (the green one with a small R_{56}). The relative delay time of double pulses is demonstrated as $\Delta t = \Delta R_{56}/(2c)$, where ΔR_{56} is the difference of two chicanes. In order to delay the front pulse to the following RF bucket, the required ΔR_{56} is about 200 mm.

The septum magnet in the nested chicane is used to bend the electron pulse of higher energy, but it has little influence on the pulse of lower energy. The orbit separation of the double pulses at the position of the septum is about 1 cm if we choose suitable parameters of the L-band and the chicanes.

3 Double-pulse scheme at the SXFEL

SXFEL is a test facility based on two-stage cascaded HGHG with ‘fresh bunch’ technology, as shown in Fig. 2. It consists of an injector, a laser heater system, an X-band as the linearizer, a main accelerator system (L1, L2 and L3) and two bunch compressor chicanes (BC1 and BC2). An 8-ps-length electron beam is generated in a 1.6-cell S-band photocathode gun with the bunch charge of 500 pC and the peak current of 50 A. The electron beam is accelerated to 130 MeV in the injector and sent to the laser heater, which is used to increase the slice energy spread (from 1 to 20 keV) to suppress the longitudinal microbunching instability. The L1 (S-band) accelerates the electron beam to 210 MeV, and the linearizer offsets the RF effect. The electron beam is compressed by 5 times in the first bunch compressor (BC1). Then, the beam is boosted again to 420 MeV in L2 (S-band) and compressed twice further in the second bunch compressor (BC2). The last accelerator section (L3, C-band) accelerates the electron beam to 840 MeV, and the beam is sent to the FEL part for soft X-ray generation at the wavelength of 8.8 nm.

Three-dimensional start-to-end simulation of the electron beam is carried out with ASTRA [25] for simulating the injector with space charge effect taking into account, and ELEGANT [26] for simulating the remainder of the linac, considering the longitudinal space charge effect (LSC), the coherent synchrotron radiation effect (CSR) and the longitudinal wake field. Main parameters of the SXFEL are listed in Table 1.

In our new scheme, we generate double electron pulses in the photocathode gun with the separation of 350.14 ps (the same as the period of S-band at 2856 MHz), ensuring the same phase and field so that the double pulses meet in the injector. When they are accelerated in L1 and linearized in the X-band, the double electron pulses are of the same small chirp. In order to introduce energy difference between the double electron pulses, an L-band (1428 MHz) is inserted upstream of the first chicane. When the double pulses pass through the L-band, the front pulse loses energy as it meets the trough of electric field, while the back one

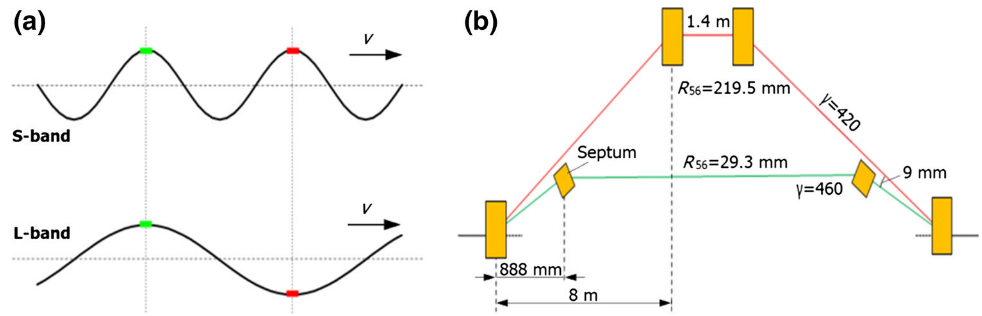

Fig. 1 Phase of the double pulses (**a**) and layout of the nested chicane (**b**)

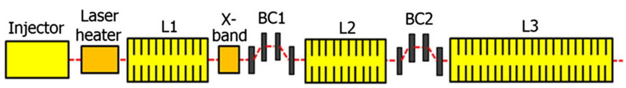

Fig. 2 Layout of SXFEL acceleration and compression system

Table 1 Main linac parameters of the SXFEL

Electron beam energy (MeV)	840
Slice energy spread (keV)	200
Peak current (A)	600
Charge (pC)	500
Bunch length (FWHM) (fs)	800
Transverse emittance (mm·mrad)	1
Transverse beam size (rms) (mm)	0.1
R_{56} in BC1 (mm)	48
R_{56} in BC2 (mm)	20
Radiation wavelength at the 2nd stage (nm)	8.8

achieves energy as it meets the peak of accelerating field (Fig. 1a). The longitudinal phase space of each pulse is shown in Fig. 3 at the injector and L-band exits. One sees that the double pulses are the same in the injector, while an energy difference of about 20 MeV is introduced in the L-band.

In order to delay the front pulse to the rear RF bucket, the nested chicane (Fig. 1) is inserted in the beamline, replacing the first bunch compressor chicane (BC1). When the double pulses in energy difference of about 20 MeV pass through the nested chicane, a different pulse of different energy passes through different orbit. The front pulse of lower energy passes through the outer chicane with a larger R_{56}. A septum is used as the second and the third dipoles of the inner chicane, so as to bend the rear pulse of higher energy, with little influence on the front pulse. The R_{56} of the outer orbit is 219.5 mm, and the inner one is 20.3 mm. Although the R_{56} of the outer chicane is large, the front pulse would not be compressed much as the chirp of each pulse is small. Figure 4 shows the phase space of the double pulses at the exit of the nested chicane. One can see that the front pulse is delayed to the rear RF bucket. The front pulse is compressed about three times, and the separation of double pulses is about 20 ps.

After the nested chicane, the double pulses are accelerated in L2, where a chirp is added and an X-band is inserted to tune the relative chirp of each pulse. The double pulses are compressed in the second bunch compressor chicane. Varying the amplitude of the X-band in L2 can tune the compression ratio of each pulse. Changing R_{56} of the chicane can tune the separation of the double pulses continuously from 0 ps to several ps. Because of the longitudinal wake and energy difference of double pulses, it is difficult to compress the beam to high peak current in the normal way. If we increase the R_{56} of the chicane, the separation of double pulses reduces from 20 to 0 ps and double pulses overlap each other. However, if we continuously increase the R_{56} of the chicane, the double pulses

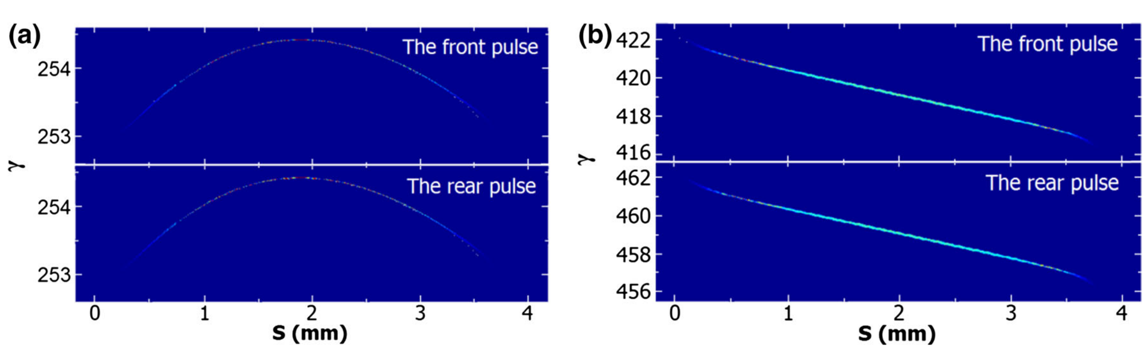

Fig. 3 Phase space of double electron pulses at exit of the injector (**a**) and L-band (**b**)

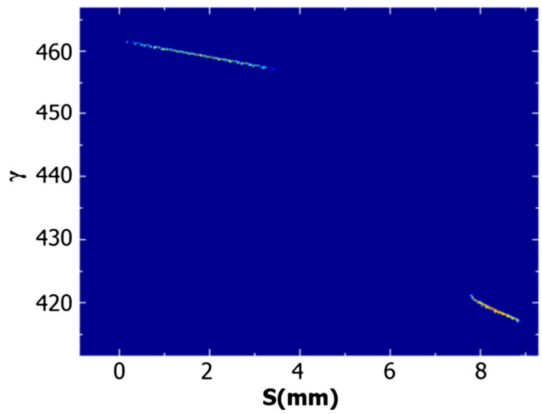

Fig. 4 Phase space of the double pulses at the exit of the nested chicane

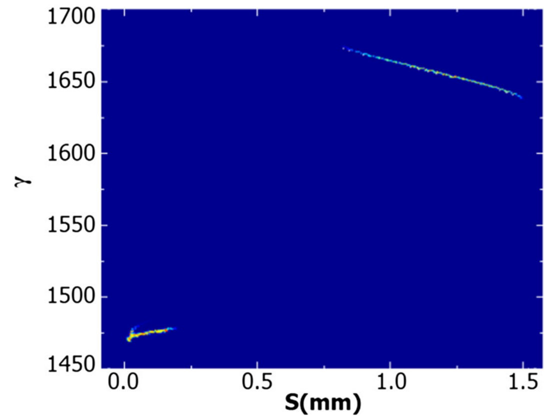

Fig. 6 Phase space of the double pulses at the exit of linac

are separated again, which is the overbunch technique. The double pulses exchange their position, while each pulse is compressed normally. The double pulses are separated in transverse so that the beam dynamic of each pulse is not destroyed in the chicane. The phase spaces of the double pulses at the exit of L2 and the second chicane are shown in Fig. 5.

Finally, the double pulses are further accelerated in L3 to a higher energy. The energy difference of the double pulses is about 90 MeV, and the separation of the double pulses is about 4 ps. The peak current of each pulse is 300 and 500 A, respectively. By varying the separation of double pulses, the energy and peak current changes. Phase space of the double pulses at the linac end is shown in Fig. 6.

As mentioned above, the emittance spoiler technique is the easiest way to generate double pulses. One just needs to insert a double-slot foil in the middle of the chicane, and to vary the pulse length and separation by changing the slot width and spacing. Also, double-pulse scheme based on emittance spoiler technique can suppress the beam energy jitter, which is suitable for the cascaded HGHG scheme based on double-pulse scheme [27]. However, limitation of the separation is that the double pulses are of the same pulse length and energy. The charge of each pulse is 100–200 pC, and the separation is about 200 fs. With the double pulses, scheme generated in the injector in the same RF bucket is suitable for generation of the two-color radiations. The charge of each pulse is related to the power of the drive laser. The interpulse spacing of the double pulses can be varied easily, just by changing R_{56} of the second chicane. The phase space of the existing methods generating the double-pulse scheme is shown in Fig. 7. One sees that the charge of both existing methods is low and the pulse length is limited to several-hundred fs. The interpulse spacing of the double pulses is convenient to change, but still limited to several-hundred fs. Our new scheme provides high charge (500 pC) in each pulse and tunable interpulse spacing of several picoseconds. However, the scheme is much complex comparing to the existing methods (μ).

It should be noted that a similar work has been carried out using a nested chicane to control the separation of twin pulses [28]. The authors insert a chicane in the middle of

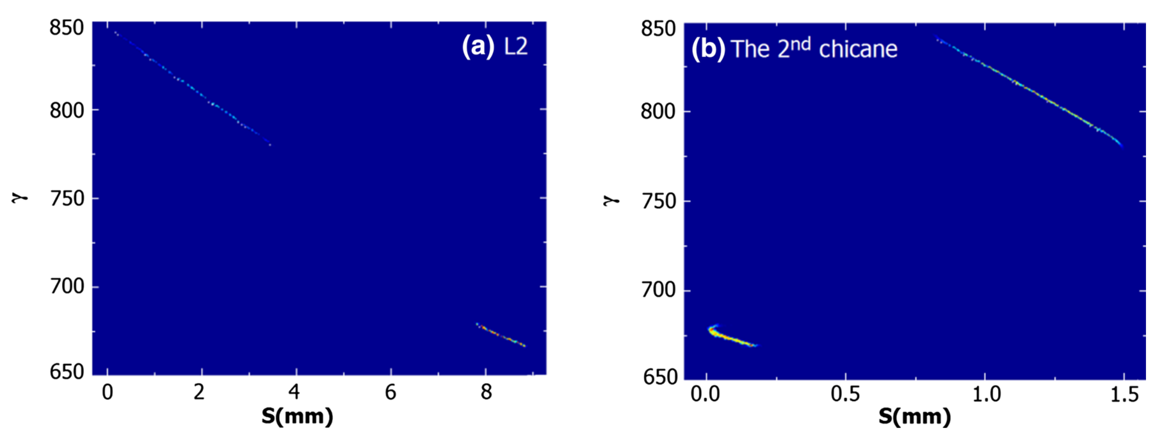

Fig. 5 Phase space of the double pulses at the exit of L2 (a) and the second chicane (b)

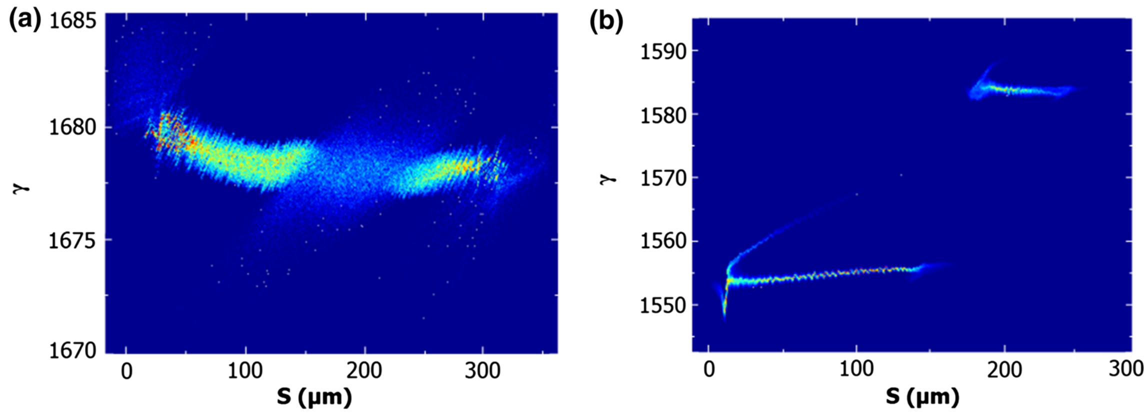

Fig. 7 Phase space of the existing method at the exit of SXFEL linac based on **a** emittance spoiler technique and **b** double pulses generated in the photocathode gun in the same RF bucket

another chicane, as the time delay system, increasing the separation of twin pulses from sub-ps to several-ps level. However, our scheme differs from Ref. [28]. in that we delay the double pulses from two RF buckets, while they generate two bunches in the same buckets. This allows us to generate double pulses with larger charge and longer pulse length.

4 Conclusion

In this paper, we present a new method to generate double-pulse scheme at the Shanghai soft X-ray free electron laser facility. This scheme can provide double pulses with long pulse length and separation of several ps. One can vary the separation of the double pulses continuously from 0 ps to several ps easily by varying the R_{56} of the second chicane in the linac. However, the energy and the peak current change as the delay varies. It is difficult to compress the pulses to sub-picosecond, which limits its application on femtosecond experiments. This scheme is more complex than the existing double-pulse-generation scheme, because one needs to insert an external L-band, a nested chicane and an X-band in the linac. This shall cause difficulties in the experiment's performance.

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