ISBN: 978-3-95450-265-3 doi:10.18429/JACoW-SAP2023-MOPB029

MULTI-BUNCH OPERATION MODE FOR SIMULTANEOUSLY SERVING SASE AND SEEDING FEL BEAMLINES

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Abstract

Modern free-electron laser (FEL) facilities are designed to simultaneously serve multiple undulator lines to provide x-ray pulses with high peak power and tunable wavelengths. To satisfy different scientific demands, it is preferred to make the separate undulator lines work under different FEL schemes, such as the self-amplified spontaneous emission (SASE) scheme and the echo-enabled harmonic generation (EEHG) scheme. However, different FEL schemes have different requirements on the beam longitudinal distribution. Here, we propose to use multiple bunches to simultaneously serve the undulator lines and put the bunches at different acceleration phase to change the bunch length with two compressor chicanes. The acceleration phase for each bunch is varied by adjusting the time delays of the photocathode drive laser pulses with the accelerator settings unchanged. The start-to-end simulation demonstrates that a fs bunch with high peak current can be produced to serve the SASE line while a bunch with hundred-of-fs length and uniform current distribution can be produced to serve the EEHG line. The FEL performances are simulated and discussed.

INTRODUCTION

Modern FEL facilities are designed to operate two or more undulator lines simultaneously with a single-pass linac-based machine and exploit beam distribution systems to send electron bunches to their respective beamlines. In normal conducting linacs, limited by the low repetition rate, only a modest average brightness can be provided. It is necessary to accelerate two electron bunches in the same radiofrequency (RF) macropulse to increase the repetition rate, as in SwissFEL [1]. In superconducting RF linacs, megahertz (MHz) electron bunches can be provided and the photon average brightness is greatly enhanced. The MHz electron bunches are then sent to different undulator lines in a group mode as in European XFEL [2] and FLASH [3] or one by one as in LCLS-II [4] and SHINE [5].

To extend the application range of FEL generated light, it is preferred to operate different undulator lines under different schemes to provide either sub-fs or fully longitudinally coherent pulses. However, different FEL schemes have different requirements on the beam longitudinal distribution. The SASE scheme requires fs electron bunch with high peak current to shorten the saturation length and increase the peak power, while seeding schemes require bunches with hundred-of-fs length and uniform current distribution to improve the modulation stability. To satisfy the requirements of different FEL schemes, one solution is to accelerate the bunches at different accelerating phases and change the bunch lengths with compressor chicanes. The acceleration phase for each bunch can be varied by changing the microwave amplitude and phase as has been done in SwissFEL [1] and FLASH [6]. However, in superconducting RF linacs with MHz repetition rate of macropulses, changing the amplitude and phase of different macropulses is a challenge and might affect the machine stability.

In this paper, we study the multi-bunch scheme and change the acceleration phase of each bunch by adjusting the time delays of the photocathode drive laser. A bunch with hundred-of-fs length and uniform current distribution is produced for EEHG lasing while a sub-fs bunch with high peak current can be produced for SASE lasing under the same machine parameters.

MULTI-BUNCH SCHEME

The multi-bunch scheme has been studied both theoretically and experimentally [7-10]. Here, we concentrate on modulating the longitudinal distribution of the bunches into different shapes to simultaneously maximize the radiation performance of different FEL schemes in different undulator lines. We take the typical two-stage compression beamline at S3FEL as an example, as shown in Fig. 1. Laser pulses with a repetition rate of 1 MHz illuminate the photocathode to produce electron bunches. Two chicanes are used to compress the bunch length from several picoseconds to tens of femtoseconds. After acceleration to 2.5 GeV, the bunches are distributed to separate undulator lines respectively. Two of the undulator lines exploit the SASE scheme to lase and the other two exploit the EEHG scheme. To simultaneously maximize the radiation performance of all the undulator lines, the bunches directed into different undulator lines are put on different acceleration phase and thus different compression just by changing the time delay of the photocathode laser pulses.

Injector

The injector includes a normal-conducting continuous-wave (CW) RF gun operating at 217 MHz (6th sub-

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ISBN: 978-3-95450-265-3   doi:10.18429/JACoW-SAP2023-MOPB029

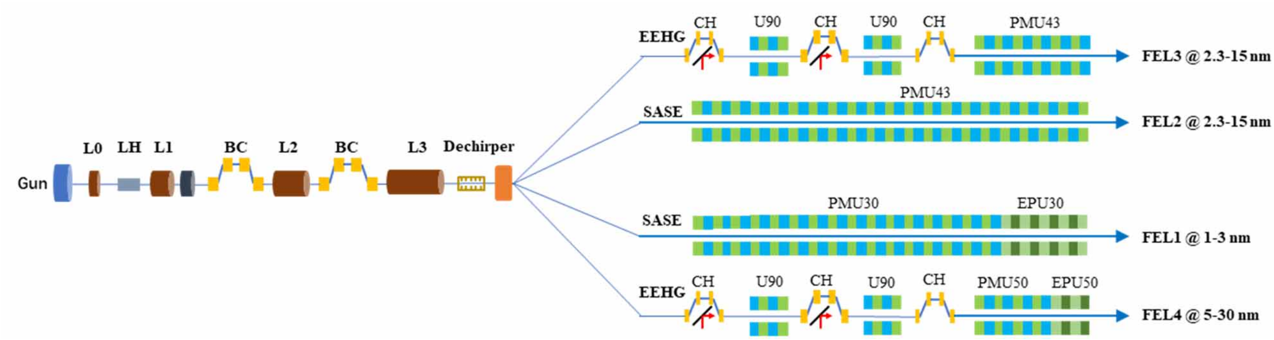

Figure 1: Schematic layout of S3FEL. Electron bunches are extracted from a VHF gun and subsequently accelerated in super-conducting Linac sections and compressed in the two magnetic chicanes. The beam is accelerated to 2.5 GeV before directed to different undulator lines.

harmonic of 1.3 GHz), a 1.3 GHz buncher and a superconducting acceleration module. The beam dynamics in the injector for a 100 pC bunch charge is simulated by ASTRA (Floettmann, 2017). The detailed parameters of the injector are shown in Table 1.

Table 1: Parameters of the Injector

Parameter	Value	Unit
Drive laser		
Beam charge	100	pC
Laser temporal profile	Flat-top	
Laser FWHM L_t	29	ps
Flat-top edge width r_t	1	ps
Transverse RMS size	0.19	mm
Thermal emittance	0.19	µm
VHF gun		
RF frequency of gun	217	MHz
Acceleration gradient	26	MV/m
Injection phase	-5	degree
Buncher		
RF frequency of buncher	1.3	GHz
Acceleration gradient	1.8	MV/m
Acceleration phase	-90	degree
Cavity position	0.86	m
Eight-cavity cryomodule		
RF frequency of cavities	1.3	GHz
1st cavity position	2.76	m
1st cavity gradient	15	MV/m
1st cavity phase	-5	degree
2nd cavity gradient	0	MV/m
3rd-8th cavities gradient	26	MV/m
3rd-8th cavities phase	0	degree

The bunch arrival time at the exit of the injector, which may change the downstream compression, depends on the injection time of the photocathode drive laser. Figure 2 gives the arrival time of the bunches with different injection time in the gun, relative to the arrival time of the nominal bunch. An evident negative correlation between the beam arrival time and the injection time offset results from the -90° acceleration phase of the velocity buncher. Figure 2b gives the relative arrival time along the beamline of the bunches with injection time offsets 5 ps and -5 ps. The bunch that arrives earlier will obtain a lower velocity in the buncher. After passing through the drift space between the buncher and the first acceleration section, the bunch will be delayed relative to the nominal bunch.

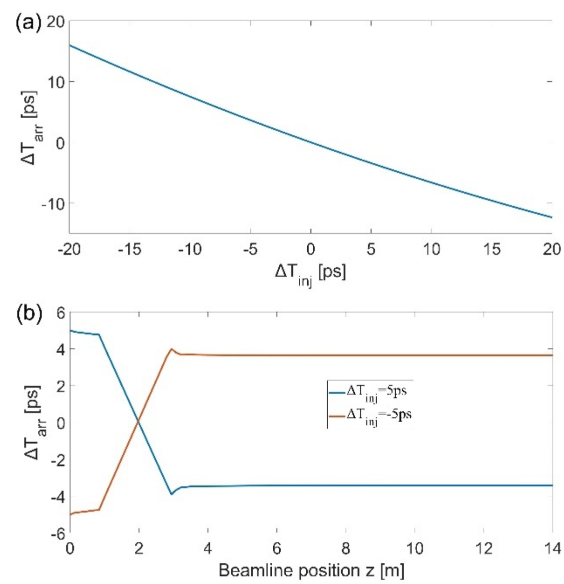

Figure 2: (a) Relative beam arrival time for different injection time offset. (b) Relative beam arrival time along the beamline for injection time offset 5 ps and -5 ps.

Main Linac

Negative energy chirp is imposed on the beam in the acceleration module L1 and L2. After the two-stage compression, the beam is then accelerated to 2.5 GeV in the acceleration module L3. First of all, 1D simulation code LiTrack (Bane & Emma, 2005) is used to optimize the acceleration and compression parameters to obtain a bunch with hundred-of-fs length and uniform current distribution for EEHG lasing. The code Elegant (Borland, 2000) is then used to simulate the complete beam dynamics. The detailed parameters of the main linac are given in Table 2. Figure 3a shows the longitudinal phase space and current distribution of the nominal EEHG bunch. The electron

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bunches with different injection time will experience different compression due to the change of the acceleration phase. Figure 3b shows the longitudinal phase space and the current distribution of the bunch at the end of the main linac with 20 ps gun injection time offset, which we call the SASE bunch here. The change of the harmonic cavity phase makes the compression nonlinear and a high peak current appears after the second compression chicane (BC2). After the electron beam exits the BC2, longitudinal space charge force within the high current spike induces a strong energy chirp [11], which can be utilized to further compress the spike with a positive R56 in a dogleg, reaching a peak current of above 8 kA. To avoid too large energy chirp inside the current spike, here, the charge of the SASE bunch is reduced to 60 pC.

Table 2: Parameters of the Main Linac

Parameter	Value	Unit
L1 voltage	246.3	MV
L1 phase	-18.4	degree
Lc voltage	60.2	MV
Lc phase	-159.7	degree
BC1 R56	-82.4	mm
BC1 beam energy	269.5	MeV
L2 voltage	931.3	MV
L2 phase	-13.2	degree
BC2 R56	-14	mm
BC2 beam energy	1175.8	MeV
L3 voltage	1335	MV
L3 phase	0	degree
L3 exit beam energy	2500	MeV

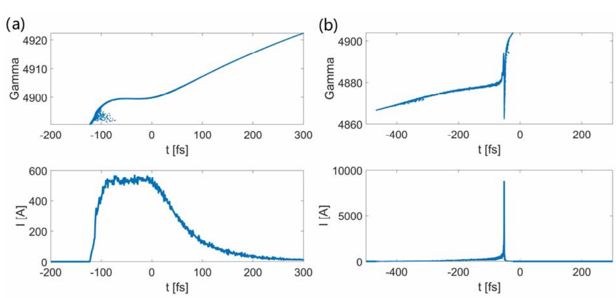

Figure 3: Longitudinal phase space and current distribution of the (a) EEHG bunch (100 pC) and (b) SASE bunch (60 pC) at the end of the main linac.

To avoid the emittance dilution due to the CSR effect, the strengths of the quadrupoles are optimized. The normalized emittance of the EEHG bunch and the SASE bunch can be both maintained smaller than 0.4 µm.

FEL PERFORMANCE

The EEHG bunch and SASE bunch are directed to the EEHG undulator line and SASE undulator line respectively. Figure 4 shows the FEL power and the spectrum of the two kinds of bunches. The EEHG spectrum is typically clean and the linewidth is ~1.8e-4. The SASE pulse width is ~380 as and the peak power is ~29 GW, which offers an opportunity for studying the ultrafast processes.

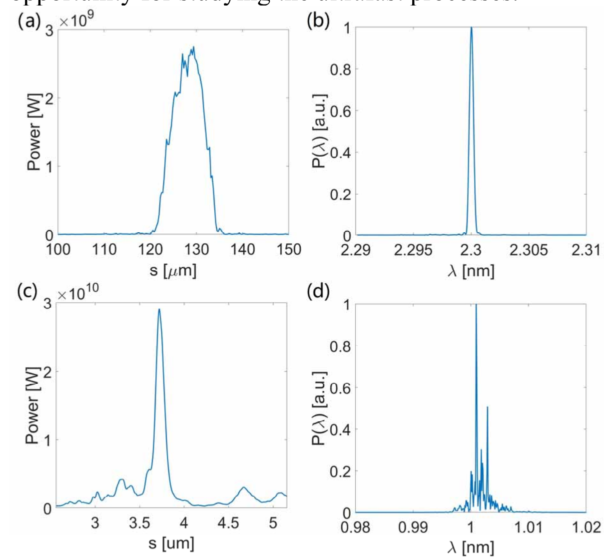

Figure 4: FEL power and spectrum. (a) EEHG power and (b) EEHG spectrum from the EEHG bunch. (c) SASE power and (d) SASE spectrum from the SASE bunch. The full width of half maximum (FWHM) of the SASE pulse is ~380 as.

CONCLUSION

The start-to-end simulation shows that the EEHG scheme and the SASE scheme can be operated simultaneously in different undulator lines, served by different electron bunches with different longitudinal length and shape. Taking advantage of the space charge force, a 380 as FEL pulse at 1 nm with peak power of 29 GW can be generated.

ACKNOWLEDGEMENTS

We wish to thank Chao Feng and Zhen Wang for their many interesting discussions. This work was supported by the National Key R&D Program of China (Grant No. 2018YFE0203000) and the National Natural Science Foundation of China (22288201).

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