

Velocity bunching for the linac of Shanghai Deep UV FEL facility

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Abstract High brightness electron beam is one of the main goals of the research and development effort in RF photo-injectors. Compared with the normally used magnetic chicane, an alternative scheme, commonly known as ‘velocity bunching’, has been proposed as a tool to compress electron beam pulses in modern high brightness photo-injector sources. This paper presents numerical optimization systematically and the first attempt to demonstrate the velocity bunching scheme on SDUV-FEL linac experimentally. The relationship between the degree of bunching and the off-crest phase of the accelerating structure is explored experimentally. Velocity bunching operating mode illustrates flexible performances with an intrinsic machine jitter, which agrees well with the theoretical prediction.

Key words Linear accelerator (linac), Velocity bunching, Bunch length, Compression

1 Introduction

High brightness beams have various applications in areas of short wavelength Self-Amplified Spontaneous Emission (SASE), seeded FEL scheme, Thompson-scattering generation of short X-ray pulses, and are used in the advanced accelerator technologies of beam injection into high-gradient accelerators and plasma wake-field drivers. An alternative scheme which could simultaneously preserve the phase space quality and shorten the bunch length^[1], commonly known as ‘velocity bunching’, has been proposed as an injector for X-ray FEL facility. This scheme is based on the phase slippage between the electrons and

the RF wave for a non-relativistic beam, and the compression happens in a rectilinear section so that the damage suffered by travelling along curving trajectories is avoided. This novel compression scheme has been recently observed and studied experimentally at SPARC in Italy^[2], the Neptune laboratory in UCLA^[3], and the FLASH in DESY^[4].

The Shanghai Deep UV-FEL (SDUV-FEL) facility, a high gain harmonic generation (HG) FEL test facility, is now a platform for novel FEL principle verification, such as cascaded HG, EEHG (echo-enabled harmonic generation), etc^[5]. As shown in Fig.1, the accelerator system of the SDUV-FEL test facility consists of a photo-injector and a linac.

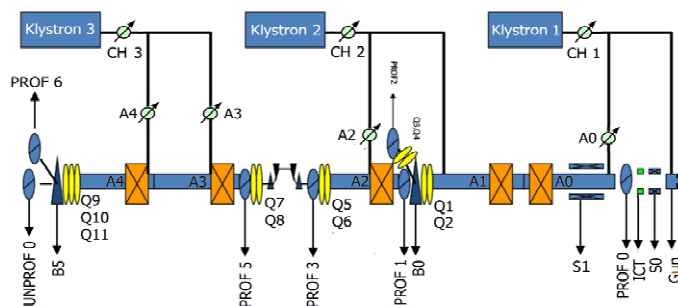


Fig.1 Layout scheme for the linac of SDUV_FEL facility.

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For nominal operation, the linac provides a 250-pC bunch charge with a projected transverse emittance of less than 5 mm-mrad. A 3.6-ps (rms) laser is used for driving the photo cathode. An electron bunch from the RF gun is injected into the first accelerating structure (A0), which is surrounded by focusing coils for emittance matching. After off-crest acceleration through the following two structures (A1&A2), the chirped electron bunch is compressed when it passes through the magnetic chicane. The induced correlated energy spread can be partly or fully compensated by the A3&A4 accelerating structures. In present conditions, the RF phase for each accelerating structure can be tuned individually and the energy gain for each accelerating structure before the magnetic chicane can be determined by the two energy spectrometers.

In this paper, we report the numerical simulations and the experiment to demonstrate the velocity bunching scheme on SDUV-FEL linac. The numerical optimization indicates that, for velocity bunching scheme, the beam energy jitter is the main disadvantage compared with the magnetic bunch compression scheme. The experiment shows that a 1.4-ps electron beam can be obtained when the A0 accelerating structure is 70 degree off-crest.

2 Simulation of velocity bunching

Using 3D space charge code ASTRA^[6], the initial 3.6-ps electron bunch with uniform transverse distribution is optimized for emittance matching. The maximum accelerating field for the photo cathode gun is 80 MV/m and the RF phase is shifted to obtain the maximum energy gain. The gradient for the SLAC type travelling wave accelerating structures A0 and A1&A2 is 10 MV/m while that of the A3&A4 is 16 MV/m because of the powerful 80 MW Klystron 3.

2.1 Optimization for Velocity bunching

To keep the oscillations under control during the velocity bunching, the beam has to be injected into the RF structure with a matched laminar waist, and the beam envelope has to be matched to the accelerating and focusing gradients, so as to stay close to an

equilibrium mode. For SDUV-FEL linac, the simulation results confirm that velocity bunching can be an efficient way to increase the peak current of the beam. To obtain the equivalent bunch length as the normal operation with the magnetic chicane compression scheme^[7], the RF phase of the A0 accelerating structure is shifted to 70 degree off crest and the evolution of bunch length and average beam energy along the beam line is illustrated in Fig.2.

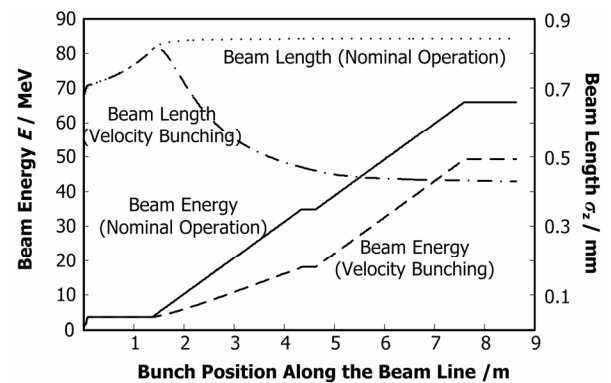


Fig.2 Beam evolution along the beam line.

In the velocity bunching scheme, an ASTRA simulation shows that the bunch length initially increases in the drift region between the RF gun and the compressing traveling wave linac section, because of the space charge effect of the 250-pC bunch charge. After two accelerating structures, the electron beam length is compressed from 0.82 mm to 0.43 mm and the average beam energy is about 15 MeV less than that in nominal operation. The longitudinal phase space and temporal distribution along the bunch at the exit of injector are shown in Fig.3. Compared with the nominal operation, the peak current is two times larger accordingly and the chirped energy spread induced during the velocity bunching are clearly shown in the results.

The maximum energy gain in velocity bunching scheme is limited because of the off-crest accelerating process. Meanwhile, the correlated energy spread induced by velocity bunching can be preserved (Fig.3b) and this “chirped” beam can be further bunched using traditional magnetic chicane compression scheme. This kind of novel multistage compression is different from the normal two stages magnetic chicane compression, and has been

considered to provide high brightness electron beam for FEL facility^[8]. So, for hybrid compression scheme, the limitation of the maximum energy gain of the velocity bunching is not as bad as it appears.

2.2 Stability simulation for velocity bunching

FEL operations set stringent requirements for the stability of the linac output parameters, such as the electron bunch arrival time, the peak current and the average energy. For velocity bunching scheme, off crest accelerating implies poor stability of the machine^[9]. For SDUV-FEL linac, photo cathode gun

shares the same klystron with the A0 accelerating structure. This specific configuration makes the machine jitter even more complicated and should be distinguished and studied carefully.

The jitter simulation results for the nominal operation and the velocity bunching scheme are listed in Table 1, together with the results of different RF power configurations. In the simulation, 50 random initial distributions are used for dynamic tracking, with the 0.5° phase random error, 0.1% RF amplitude error and 150 fs driving laser arrival time error.

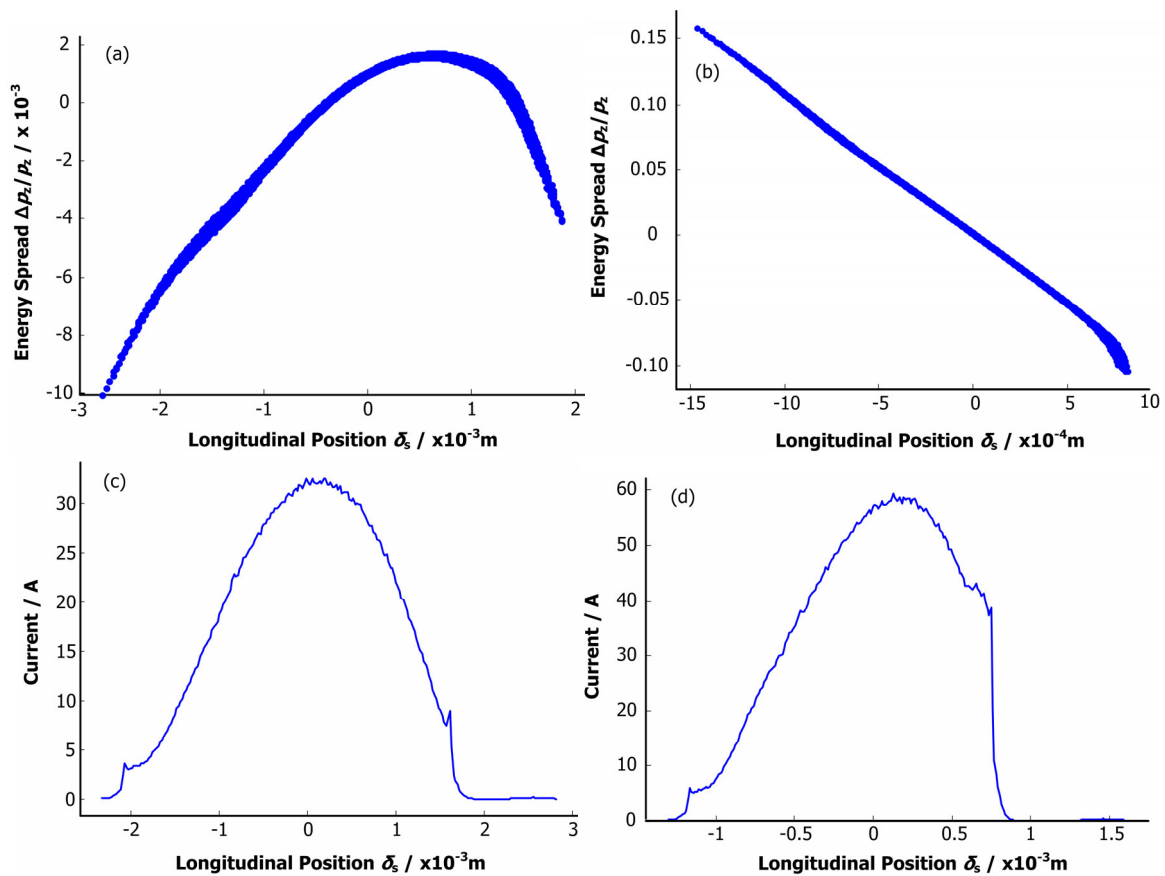


Fig.3 Longitudinal phase space in nominal operation (a), Longitudinal phase space in velocity bunching (b), beam current distribution in nominal operation (c) and beam current distribution in velocity bunching (d).

Table1 Bunch parameter and jitter simulation results (the rms jitter results are shown in the brackets)

Schemes	Mean energy / MeV	Energy spread / keV	Arrival time / degree	Bunch length / mm
Nominal	65.97 (0.033)	96.3(6.14)	281.4(0.283)	0.839(0.0096)
Nominal*	65.97(0.037)	96.5(9.03)	281.5(0.254)	0.839(0.008)
Velocity bunching	48.7 (0.142)	743.8(18)	294.3(0.137)	0.430(0.010)
Velocity bunching*	48.7(0.249)	742.5(16)	294.3(0.555)	0.430(0.011)

The apostrophe means separate power feed.

For the nominal operation scheme, regardless of the RF power feed configurations, the machine jitter does not result in a significant difference. For velocity bunching scheme, however, the coupling effect from the off-crest accelerating makes the arrival time jitter much better than the option in which the power is provided individually. Even in the presence of this coupling effect, the average beam energy jitter is significant for the velocity bunching mode, almost 0.3% at the exit of the first two accelerating structures as shown in the simulation results. It should be noted that, this average energy jitter from velocity bunching scheme can also be shrunk if always accelerate the beam on the crest after the first accelerating structure.

3 Experimental demonstrations of velocity bunching on SDUV-FEL linac

To justify the theoretic model and the simulation results in Section 2, an experiment for velocity bunching scheme is carried out on SDUV-FEL linac. Off-crest acceleration for velocity bunching is accomplished with a high power phase shifter. After carefully adjusting the emittance compensation solenoid and the focusing coils, zero-phasing method^[10] is adopted for measuring the bunch length using the second accelerating structure A1. Fig.4 gives the average beam energy and the energy spread at different RF phases of the second accelerating structure A1, in which the energy spread refers to the bunch length according to the RF chirp of the accelerating structure. The consistence of simulation results and experiment data suggests that the bunch length is compressed from 3.6 ps to 1.4 ps as expected.

Using this method, the bunch length is determined according to different settings of the phase shifter, which corresponds to different compression factors of the velocity bunching scheme. The results are shown in Fig.5. For higher compression factor with larger off-crest RF phase, the inconsistency of the experiment and the simulation results comes from the inaccuracy in energy spread measurement.

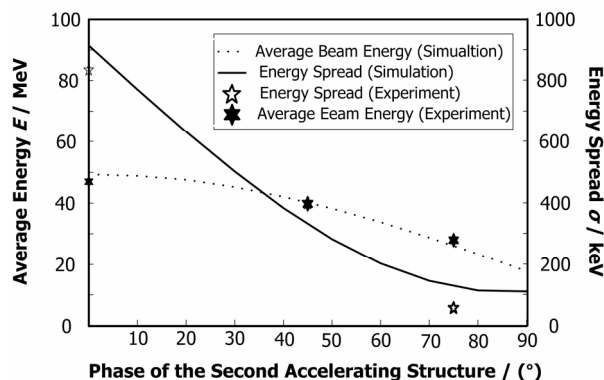


Fig.4 Average beam energy and the energy spread for different RF phases of the second accelerating structure A1.

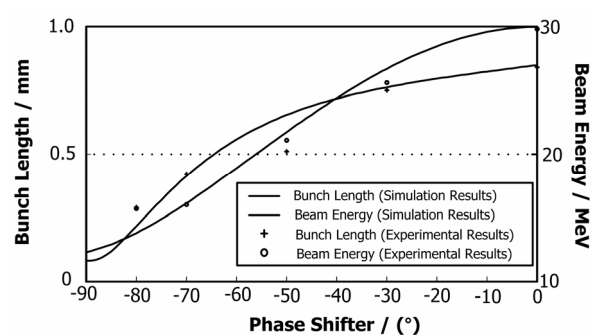


Fig.5 Bunch length of simulation results and experimental results according to different phase shifter setting. Velocity bunching experimental and simulation results based on SDUV-FEL facility.

Fig.6 shows the average energy jitter results obtained from the nominal operation and the velocity bunching scheme. Larger average energy jitter of the velocity bunching scheme is confirmed by statistical analysis of the experimental data, which agrees well with the simulation results in Section 2.

Transverse emittance is also crucial for FEL facility because of the effective interaction between the electron beam and the laser. For velocity bunching mode in our experiment, measurement of the projected transverse emittance is not accurate using the traditional scanning quadrupole magnet method because of the large energy spread from the energy modulation process. The slice transverse emittance measurement should be used and will be accomplished in the near future using the dipole magnet B0 as a slicer^[11].

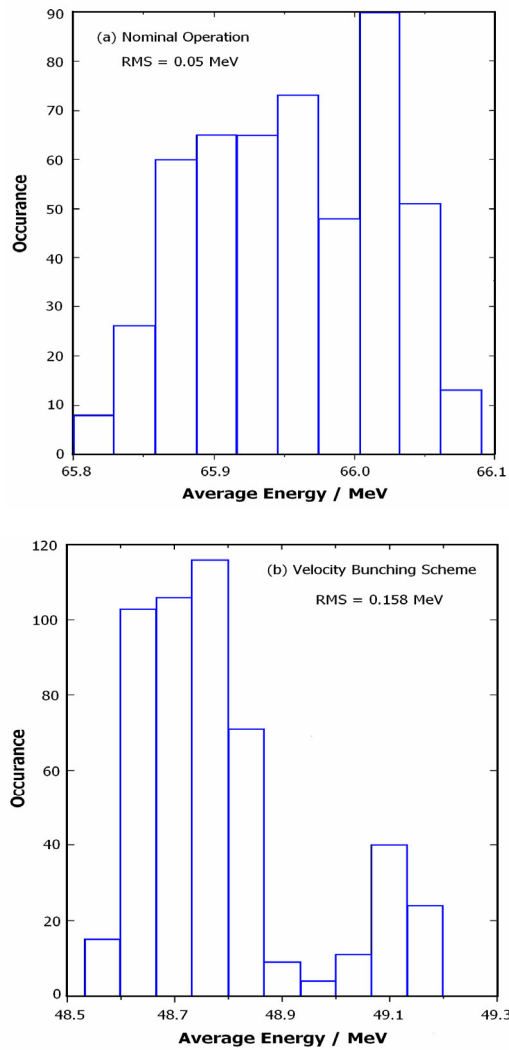


Fig.6 Histogram of 500 experimental data of average energy under nominal operation and velocity bunching scheme.

4 Conclusion

The velocity bunching scheme is optimized and demonstrated on the SDUV-FEL facility. Machine jitter for velocity bunching scheme, important but surprisingly lack of literature, is studied

systematically. The results from simulation and experiment are consistent and this compression scheme can also be applied for Shanghai soft X-ray Free Electron Laser (SXFEL) facility.

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