Simulation study of a photo-injector for brightness improvement in Thomson scattering X-ray source via ballistic bunching *

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Abstract: Increasing the peak brightness is beneficial to various applications of the Thomson scattering X-ray source. A higher peak brightness of the scattered X-ray pulse demands a shorter scattering electron beam realized by beam compression in the electron beam-line. In this article, we study the possibility of compressing the electron beam in a typical S-band normal conducting photo-injector via ballistic bunching, through just adding a short RF linac section right behind the RF gun, so as to improve the peak brightness of the scattered x-ray pulse. Numerical optimization by ASTRA demonstrates that the peak current can increase from 50 A to > 300 A for a 500 pC, 10 ps FWHM electron pulse, while normalized transverse RMS emittance and RMS energy spread increases very little. Correspondingly, the peak brightness of the Thomson scattering X-ray source is estimated to increase about three times.

Key words: beam compression, ballistic bunching, Thomson scattering X-ray source

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1 Introduction

The Thomson scattering X-ray source with high peak brightness, proposed and demonstrated experimentally in the 1990s [1, 2], has been studied and developed worldwide. The Accelerator Laboratory of Tsinghua University has also designed and built such an X-ray source (TTX) [3–5]. The Thomson scattering X-ray source generates a high brightness, quasi-monochromatic, ultrashort X-ray pulse by scattering a laser beam off a relativistic electron beam, with applications in atomic, nuclear, particle physics, the medical field and so on. The peak brightness B_x, an important figure of merit of X-ray source performance, is defined as the number of photons/second/unit area/unit solid angle/unit bandwidth. In the case of a 180° interaction, based on some assumptions that are not so harsh, B_x (photos/s/mm^2/mrad^2/0.1%b.w.) can be expressed as [6]

$$B_x = 5.05\times10^{18}\gamma^2\frac{\lambda Q_e W_\gamma}{\Delta t_e \varepsilon_{ns}^2 x_L^2}, \quad (1)$$

where γ, Q_e, Δt_e and ε_{ns} are the Lorentz factor, total pulse charge (nC), RMS bunch duration (ps) and normalized RMS emittance (mm·mrad) of the electron beam; W_γ and x_L are the total pulse energy (J) and RMS spot size (μm) of the incident laser beam; λ is the central wavelength of the scattering X-ray pulse (μm). From Eq. (1), it is easy to know that using a high brightness electron beam taking a short pulse duration and low emittance at the same time is beneficial to improving the peak brightness of the Thomson scattering X-ray source.

As mentioned above, to produce a brilliant X-ray pulse in a Thomson scattering source, a high brightness electron beam is necessary. However, in the conditional photo-injector, an electron beam with a relatively large total charge (e.g. 100 pC to 1 nC) could not keep a short pulse duration because of the intense space charge force. Therefore, beam compression is required in the systems having demand for high brightness. Two common compression methods are magnetic compression and velocity bunching. In the magnetic compression scheme, no bunching is taken in the injector and beams are totally compressed after injector by one or more chicanes. Because of the use of a long chicane and the need of another RF linac section to compensate for the energy spread induced for compression, the device is complex and electron beam-line will be much longer than the original one. Besides, beam emittance would degrade seriously during bending in the chicane when magnetic compression is applied to a case of low energy. Velocity bunching (or

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termed phase space rotation, PSR) proposed by Serafini and Ferrario, is another option for compression [7, 8]. An electron beam is injected into the first long booster linear accelerator at the zero acceleration phase and slips back in phase up to the peak acceleration phase, it can be compressed strongly as far as the extraction happens near the synchronous velocity. PSR is effective in bunching and can avoid serious emittance degradation by surrounding the whole bunching area with a proper solenoid field to realize emittance compensation. However, the energy gain in the first booster linac is much less than a nominal case without compression, so that an extra accelerator may be required to satisfy the demand for beam energy. It also may enlarge the dimension of the original system.

Actually, velocity bunching could be carried out based on another configuration called ballistic bunching [9, 10]. Ballistic bunching can be viewed as the "thin lens" version of phase space rotation. A positive, nearly linear energy chirp is imparted to the electron beam after it passes through a short, high accelerating gradient RF cavities section, inside which the synchrotron motion is very limited, where the chirp generates compression during the beam propagation along a drift space after the RF cavities section. In the photo-injector, there is a long drift section between the RF gun and the first booster linac according to emittance compensation theory [11, 12]. It is possible to compress beams in this drift section using ballistic bunching. A normal conducting S-band photo-injector is often the choice for the Thomson scattering X-ray source. As an example, in this article we study the possibility to ballistically compress the beam in this kind of photo-injector through merely adding a short RF linac section immediately after the electron gun to the original beam-line. In Section 2, the beam-line configuration is depicted at first and the mechanism of ballistic bunching and emittance compensation in the photo-injector are reviewed then. In Section 3, the feasibility of the configuration stated in Section 2 is discussed with ASTRA [13] simulation. Optimization result shows that to a 500 pC, 10 ps FWHM electron beam, the RMS beam length can be shortened over 3.5 times (pulse peak current increases from 50 A to > 300 A) with very little normalized transverse RMS emittance and energy spread increasing. Correspondingly, the peak brightness of the Thomson scattering X-ray source is estimated to increase about three times. Under this design, even to a system in commission, beams could be bunched primarily in the photo-injector without any change to the original system except adding a short element. If the demand to pulse duration are not so short, this compression scheme may be a more convenient choice than magnetic bunching and PSR, avoiding complex design to a new magnetic compression system and enlargement of the system dimension.

2 Beam-line configuration

An injector based on a normal conducting S-band photocathode RF gun, one of the most practical designs for a high brightness beam, is described schematically in Fig. 1. An S-band BNL/KEK/SHI style 1.6 cell RF gun with a Cu photocathode inside serves as the electron source, followed by two 3-m S-band SLAC-style travelling wave sections to boost the beam to the required energy. A solenoid placed right behind the RF gun and solenoids surrounding the front half of the first linac section control the transverse size of the beam and satisfy the requirement of emittance compensation.

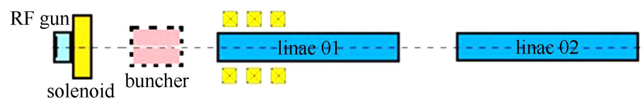

Fig. 1. (color online) The lay-out of the photo-injector considered in this article.

According to the theoretical description of the emittance compensation process, in order to damp emittance oscillations to get a low emittance beam as it is accelerated to a high energy, the beam needs to be injected into the booster linac at an envelope waist (transverse RMS divergence $\sigma'=0$) and the envelope has to be matched to the accelerating gradient of linac and the focusing strength so as to stay close to a so-called invariant envelope (IE) given by [12]

$$\sigma_{\rm IE}=\frac{1}{\gamma'}\sqrt{\frac{2I_{\rm p}}{I_{\rm A}\,(1+4\Omega^2)\,\gamma}}, \tag{2}$$

where γ' is the normalized accelerating gradient defined as $\gamma'=eE_{\rm acc}/m_{\rm e}c^2$, $E_{\rm acc}$ is the accelerating field, $I_{\rm p}$ is the beam peak current in the bunch, $I_{\rm A}=17$ kA is the Alfven current and Ω^2 equals to $eB_{\rm sol}/mc\gamma'$ to a traveling wave RF structure. In the photo-injector described above, the beam leaving the RF gun is focused immediately by the solenoid after the gun and, passing over a drift space, its envelope reaches a waist and match $\sigma_{\rm IE}$ at the entrance of the first booster linac.

The unique difference in our lay-out from the common S-band photo-injector is a short linac section placed behind the gun solenoid (shown in Fig. 1 by dashed lines) as an RF buncher to provide velocity modulation for the beam out of the gun relying on which to ballistically bunch the beam in the drift section after the buncher. The process of ballistic bunching can be illustrated, see Fig. 2. A beam is injected into the high gradient, short linear buncher near the zero acceleration phase. After leaving the buncher, a negative longitudinal monument tilt (or termed a positive chirp) is imposed over the length of the beam, see Fig. 2(b). Considering the interaction of an electron with the sinusoidal accelerating RF wave $E_z=-E_b\sin\phi$ (E_b is the peak accelerating field of the wave) and neglecting phase advance inside buncher, the chirp after the buncher can be described as [9]

$$\frac{\mathrm{d}(\partial\gamma/\gamma)}{\mathrm{d}z} = \left.\frac{\mathrm{d}(\partial\gamma/\gamma)}{\mathrm{d}z}\right|_0 - k\frac{\Delta E_m}{E_0}\left(\frac{\cos\phi}{1+\frac{\Delta E_m}{E_0}\sin\phi}\right), \quad (3)$$

where E_0 is the beam energy before entering the buncher, ΔE_m is the maximum gain available in the buncher, k is the RF wave number and $\phi=kz-\omega t+\phi_0$ is the RF phase. As a result, in the drift after buncher, particles at the tail of the beam "catch up" particles at the head gradually. When the pattern of the beam in longitude phase space becomes as Fig. 2(c) shows, the beam achieves the maximum compression. As space charge force is neglected, the drift length needed for the strongest bunching could be estimated with the chirp from Eq. (3) by [9]

$$L_d=\frac{\beta^2\gamma^2}{\left|\frac{\mathrm{d}(\partial\gamma/\gamma)}{\mathrm{d}z}\right|}. \quad (4)$$

If not promptly injected into a booster to freeze down debunching due to residual longitude space charge force, the beam will be "over-compressed", as depicted in Fig. 2(d). As stated above, ballistic bunching can be treated as a thin lens version of the phase space rotation method. Different from the long RF structure version of velocity bunching, the beam is still extracted close to the zero acceleration phase and compressed mainly in the drift section after the buncher. Taken as an example, considering a 5 MeV beam with 3 ps pulse duration and 25 keV energy spread going through a 30 cm RF buncher whose peak longitudinal accelerating field is 35 MV/m at the zero acceleration phase, the drift from the buncher to longitudinal focus is about 0.97 m, according to Eq. (3) and Eq. (4). In fact, it will be a little longer than this because of the defocusing of the longitudinal space charge force. Moreover, if the beam is not bunched so intensely that it can keep quasi-equilibrium without obvious crossover in longitude phase space, emittance growth could still be suppressed through adjusting field strengths of the gun and the linac solenoid to match the beam envelope to IE. In the following sections, the feasibility of this compression scheme will be discussed with the ASTRA simulation results.

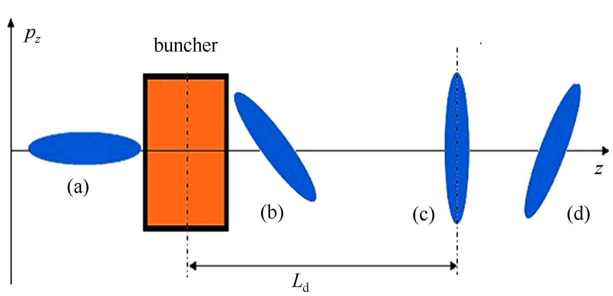

Fig. 2. (color online) The evolution of beam longitudinal phase space distribution ($z-p_z$) in the process of ballistic bunching. (a) The distribution before injection into the buncher; (b) the distribution just at the exit of the buncher; (c) the maximum compression; (d) the over-compression.

3 Numerical simulation by ASTRA

Some numerical simulations about producing relatively high charge, ultra-short pulses with the lay-out stated in Section 2 were carried out by code ASTRA. In this section, the simulation results are presented and the feasibility of the compression scheme is discussed.

3.1 Nominal case

In simulation, we consider a 500 pC total charge pulse produced. The maximum gradient at the surface of the gun cathode is set to 100 MV/m, which is a tradeoff between keeping system stability and reducing space charge force; thermal emittance is included of 0.9 mm·mrad per mm RMS of the driving laser pulse assumed a flat-top distribution with a Gaussian edge in the longitude direction and a uniform distribution in the transverse direction. Table 1 shows the detailed beam-line parameters. When the buncher does not work, i.e., no bunching happens in the injector, the optimized result to a 10 ps FWHM beam shows 0.60 mm-mrad normalized transverse RMS emittance and 50 A peak current (RMS pulse duration 2.8 ps) at the exit of the second TW section.

Table 1. Detailed beam-line parameters without buncher.

RF gun parameters	
maximum gradient/(MV/m)	100
cathode driven laser radius/mm	0.9
gun solenoid parameters	
total length/cm	22.5
center location/cm	21.4
the first booster linac parameters	
entrance location/cm	150
accelerating gradient/(MV/m)	20
solenoids length/cm	120
the second booster linac parameters	
entrance location/cm	550
accelerating gradient/(MV/m)	20

3.2 Longitude compression

The buncher chosen in this article is a conventional traveling wave structure consisting of nine cells and operating with 2π/3 mode at 2.856 MHz (about 30 cm in length). It is better for the buncher to be placed as close as possible to the RF gun in order to minimize the extent of space-charge de-bunching. But in consideration of the existence of the gun solenoid and some beam diagnostic elements behind it, the buncher is located at z=0.6 m in the simulation. To all the simulation results displayed later, all launching parameters of the electron beam and the locations of other elements except the buncher are the same as the nominal case.

As the buncher's structure and location (i.e. the length of the drift section between the buncher and the first booster linac) are specified, the final pulse duration or peak current is mainly decided by the accelerating field gradient and beam injection phase of the buncher. Choosing different buncher gradients and beam injection phases, different energy chirps shown in Eq. (3) are obtained after the beam transits the buncher. Correspondingly, a different length of drift is needed to achieve the maximum compression. As the location of the first booster linac is fixed, the beam is bunched to different compression factors at the entrance of the first linac; the bunching is frozen down rapidly once the beam is injected into the booster linac as a result of the fast gain in energy (Fig. 3).

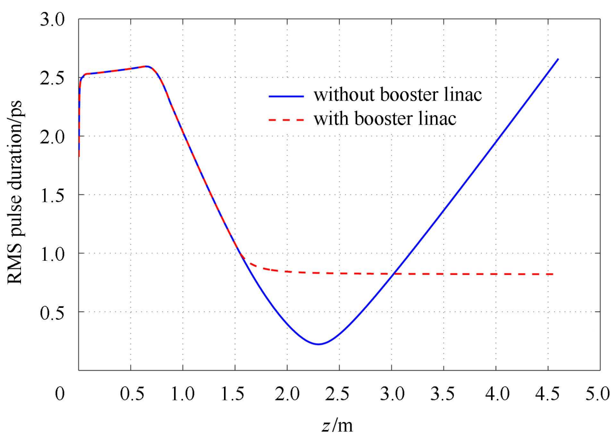

Fig. 3. (color online) Evolution of RMS pulse duration through the injector with the booster linac placed at 1.5 m (solid line), compared with over-compression when no booster exists (dashed line).

The curves explaining the relationship between the longitude RMS length of the beam at the exit of the injector and injection phase of the buncher with different buncher gradients adopted are plotted in Fig. 4. It is easy to understand that the higher gradient the buncher is driven at, the stronger bunching force exerts on the beam so that the shorter pulse duration can be obtained at the same injection phase. Obviously we cannot accept that the gradient of the buncher needed by compression is too high, considering the saving of RF power and difficulty in power shading. In fact, injecting a beam into the buncher at more "negative" phases will also exert a stronger bunching force on the beam because of a slight deceleration of the beam. For instance, injecting a beam at −106° into the buncher with a 25 MV/m gradient gets an equivalent effect on longitudinal compression to injecting beam at −98° with 35 MV/m. From Fig. 4, a wide range of beam lengths could be achieved through changing the buncher's phase with different buncher gradients and injection phases adopted, while the shortest RMS pulse duration is <300 ps. It is also worth noticing that the RF gun work point (gun gradient and launching phase) also influences the bunching process to some extent because of the difference in energy spread beam possessed before being injected into the buncher. Although optimization of the RF gun phase is not discussed here, it has been proved that the scheme presented here is effective anyway. Moreover, in many cases, the beam duration achieved above is short enough.

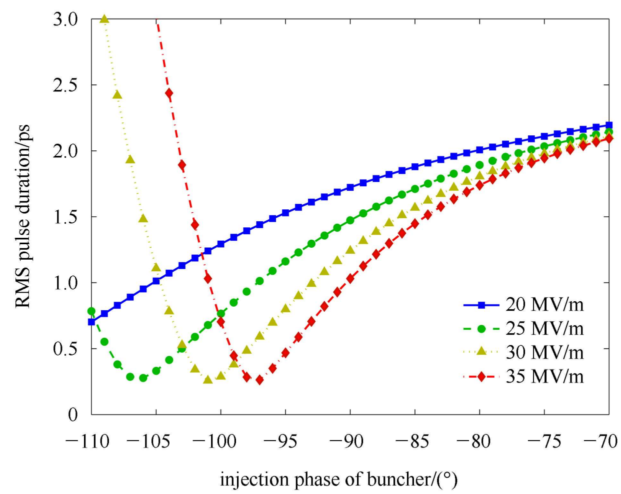

Fig. 4. (color online) RMS pulse duration at the exit of the injector as a function of the buncher injection phase with buncher gradient of 20 MV/m (blue, square), 25 MV/m (green, circle), 30 MV/m (yellow, triangle) and 35 MV/m (red, diamond).

3.3 Emittance compensation

It has already been proven that the beam length can be compressed effectively with the above scheme. But the demand for high brightness electron beams requires the beam not only to have a high peak current but also to keep a low transverse emittance. Optimization of transverse emittance can be accomplished by a careful tuning of the gun solenoid field and the first linac solenoid field. To all simulation results presented in this section, the beam's launched phase is still chosen to be the same as the nominal case. Fig. 5 presents the optimization result of the normalized RMS horizontal emittance for different longitudinal compression factors when the buncher is driven at 25 MV/m, 30 MV/m and 35 MV/m separately. As shown in Fig. 5, when pulse compression factor is less than 4 (RMS beam length is not shorter than 700 fs), no matter which buncher gradient is chosen, the transverse emittance could be compensated very well. For example, evolution of the RMS pulse duration and normalized RMS horizontal emittance for a 0.8 ps compressed beam along the injector is presented in Fig. 6, compared with those in the nominal case. According to the emittance compensation theory, if beams can keep quasi-equilibrium without obvious crossover in longitude phase space before being injected into the booster linac, emittance growth can still be well compensated through matching to IE by adjusting the gun solenoid field and the first linac solenoid field. Fig. 7 shows the longitudinal profiles of two beams with different compression factors at the entrance of the first linac. The profiles at the exit of the buncher are classified along the beam's longitudinal length, and each colored point at the entrance of the first linac indicates the location in which it is at the exit of the buncher. It is obvious from Fig. 7 that there is almost no overlap between different longitudinal slices of the beam compressed not so intensely, meaning the beam does not undergo crossover in longitudinal phase space so that the transverse emittance is able to be compensated well, while the growth of the emittance is notable because of the serious overlapping among several longitude slices at the head of the beam compressed more intensely.

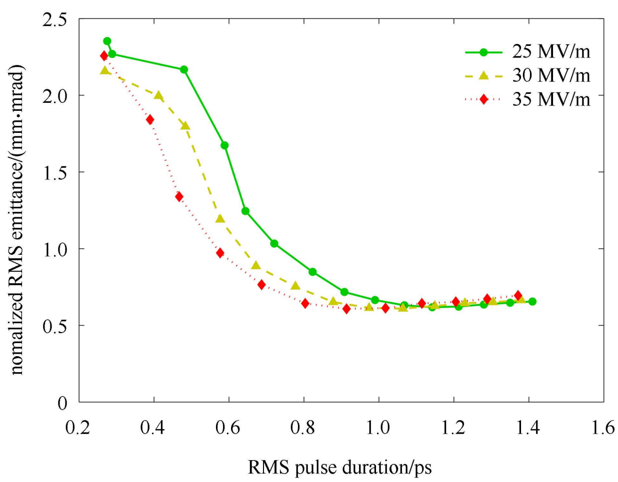

Fig. 5. (color online) Optimized normalized RMS emittance to different RMS pulse durations when the buncher gradient is chosen as 25 MV/m (green, circle), 30 MV/m (yellow, triangle) and 35 MV/m (red, diamond).

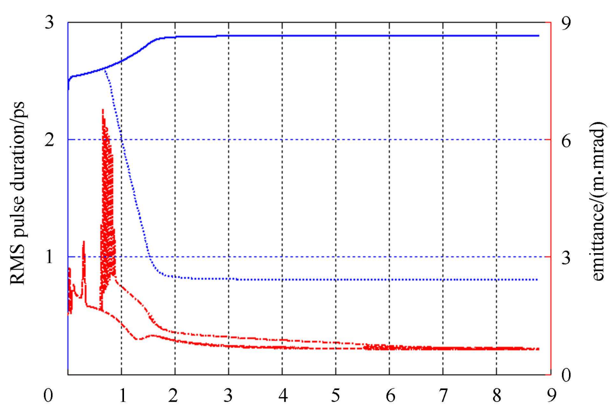

Fig. 6. (color online) RMS pulse duration (blue, left scale) and normalized RMS horizontal emittance (red, right scale) through the injector without (solid line and dashed line)/with (dotted line and dashed-dotted line) longitudinal compression.

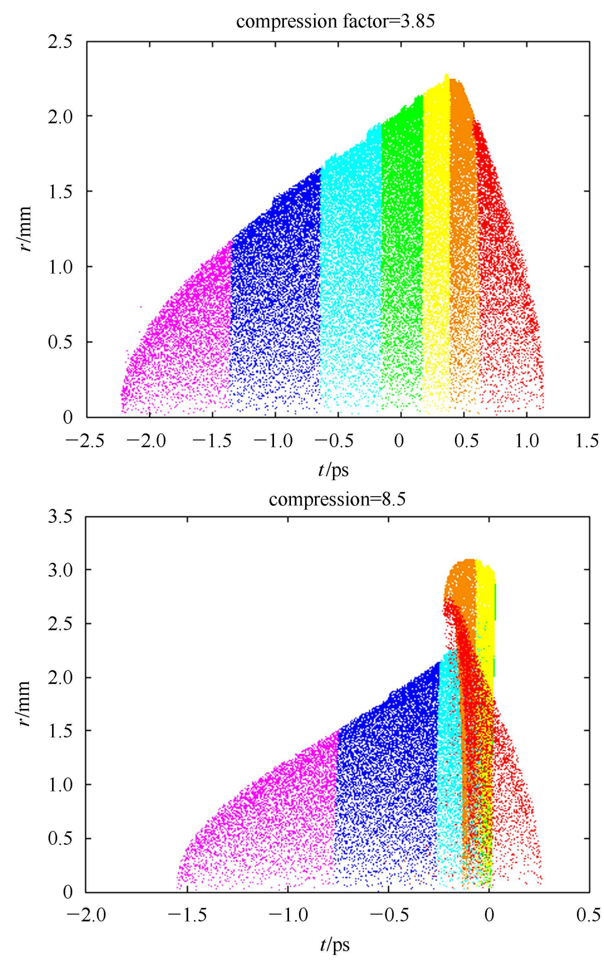

Fig. 7. (color online) Colored beam profile at the entrance of the first linac with (above) / without (below) serious overlap between different longitudinal slices.

To several situations where emittance compensated well, detailed beam qualities at the exit of the injector are shown in Table 2 ($E_b = 35$ MV/m). The transverse slice emittance and slice current distributions are shown in Fig. 8. As shown in Table 2, relative high brightness beams with >300 A peak current and low transverse emittance and low energy spread could be achieved using the compression scheme presented. Furthermore, peak brightness of scattered X-ray pulse B_x in each case is also estimated according to Eq. (1) and normalized with nominal case, shown in the last column of Table 2. The peak brightness of the scattered X-ray pulse becomes higher as the longitudinal focusing force rises. However, when the compression factor arrives at a particular value, the peak brightness starts to decrease with a stronger focusing force, because of an abrupt degradation in transverse emittance. As a tradeoff between the emittance degradation and beam compressing, this scheme allows for a peak brightness of a scattered X-ray pulse which is almost three times larger than that obtained in absence of ballistic bunching. In addition, the peak brightness calculated from Eq. (1) neglects the influence of electron beam energy spread, which actually also impairs the peak brightness of the scattered X-ray pulse. The relative energy spread shown in Table 2 is achieved when the phase of the first and the second linac set to on-crest phase, which stay as low as the nominal case. The relative energy spread can even be decreased less by tuning the phases of both booster linacs.

3.4 Jitter

To investigate the stability of the injector lay-out with ballistic bunching to operate as an electron beam injector for Thomson scattering source, the effect of RF amplitude and phase jitter has to be examined. It is possible that the photocathode gun shares the same klystron with a short buncher. The situation that errors of gun and buncher are coupled is also taken into account. Jitter simulation is based on the work point displayed at the third line in Table 2. 300 simulations with 0.5° (RMS) RF phase random error and 0.1% (RMS) RF amplitude error were carried out for each situation. The RMS fluctuations of beam arrival time and some beam parameters at the exit of the injector are listed in Table 3, compared with fluctuations in the nominal case. It should be noticed that coupling of gun and buncher makes the beam parameters jitter much better than the option where the power is provided individually, but for arrival time jitter, this improvement is very limited. From the simulation result, under the RF stability level applied here, the fluctuations of longitudinal length and transverse emittance are obviously larger than those in the nominal case. In sum, the ballistic bunching scheme raises a higher request on RF

Table 2. Electron beam quality at the exit of linac 02 and corresponding normalized peak brightness of scattered X-ray pulse under different compression forces.

compression factor	E_k/MeV	Δz_{RMS}/ps	$\varepsilon_{x,n,RMS}$/(mm·mrad)	I_{peak}/A	$\Delta E_{RMS}/E$	$B_{x,n}$
0	125.5	2.80	0.60	56	0.12%	1
3.15	125.3	0.91	0.61	238	0.17%	2.96
3.58	125.1	0.81	0.64	304	0.15%	3.00
4.19	125.0	0.69	0.76	412	0.14%	2.49

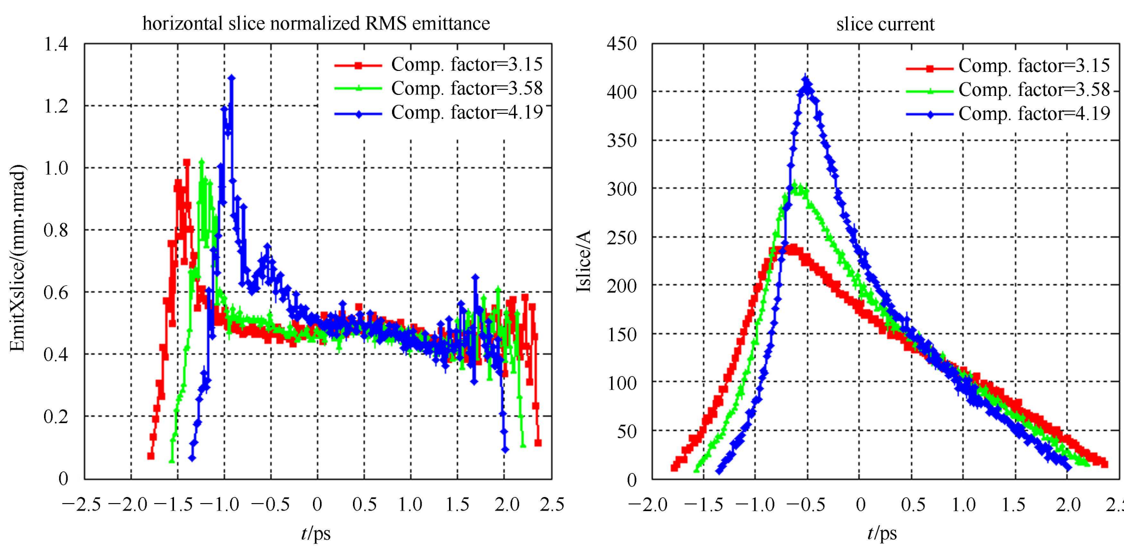

Fig. 8. (color online) Normalized RMS slice emittance (left) and slice current (right) for beams with different compression factors.

Table 3. RMS variations of beam farrival time and some beam parameters at the exit of the injector.

	t_{arrive}	Δz_{RMS}/fs	E_{k}/keV	ΔE_{RMS}/keV	$\varepsilon_{\text{x,n,RMS}}$/(mm·mrad)
no bunch	0.21°	17.20	87	33.79	0.002
uncoupled	0.43°	59.57	130	23.92	0.055
coupled	0.44°	39.84	96	23.17	0.030

stability than a nominal operation scheme, powering RF gun and buncher with the same better klystron performance.

4 Conclusion

In this article, the idea of compressing an electron beam utilizing ballistic bunching in the photo-injector for a Thomson scattering X-ray source has been proposed. Just adding a short RF buncher right behind the RF gun, bunching happens in the drift section between the gun and the first booster linac, which originally exists in the photo-injector, so that the peak current increases effectively without enlarging the scale of the system. Numerical simulation by ASTRA studied the feasibility of this scheme. The result shows that transverse emittance does not appear to have obvious degradation when the compression is not very intense; the peak brightness of the scattered X-ray is estimated to increase three times, as a tradeoff between the emittance degradation and beam compressing. Beam arrival time and beam parameters fluctuations from RF jitter can perform better when the photocathode gun and RF buncher are powered with the same klystron. Consequently, the ballistic bunching scheme proposed above has a great potential of being used on the photo-injector for the Thomson scattering X-ray source to increase an electron beam's brightness. For systems demanding several hundred amperes peak current, this scheme is a compact choice rather than magnetic bunching using chicane and phase space rotation using the whole length of the first booster linac to bunch, as it is much easier to control transverse emittance and energy spread degradation. In addition, it is also an alternative scheme to the photo-injector for other applications that require a high peak current and compactness of the system simultaneously, such as THz radiation driven by the high brightness electron beam.

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