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Generation of high brightness electron beam by brake-applied velocity bunching with a relatively low energy chirp

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ABSTRACT

Velocity bunching technique is a tool for compressing electron beams in modern high brightness photoinjector sources, which utilizes the velocity difference introduced by a traveling rf wave at a relatively low energy. It presents peculiar challenges when applied to obtain a beam with a very high current and a low transverse emittance in photoinjectors. The main difficulty is to control the emittance oscillations of the beam during high compression, which can be naturally considered as an extension of the emittance compensation process. In this paper, a brake-applied velocity bunching scheme is proposed, in which the electron bunch is injected into the accelerator with a low gradient at a deceleration phase, like "a brake is applied", afterward slips to an acceleration phase. During the entire compression process, the energy chirp induced by the rf field is mostly linear, which retains a symmetric electron beam in the temporal distribution. The key point of the new scheme is a smaller energy chirp at a lower beam energy compared with the normal velocity bunching. Besides, the beam energy chirp before compression is dominated by the linear correlation due to a relatively short laser pulse. With a symmetric bunch compression, the transverse emittance could be compensated even if the compression factor is extremely high. As to our simulation results, the peak current of the compressed beam can be above 1.8 kA for the charge of 800 pC with a good emittance compensation.

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1. Introduction

A high brightness electron beam, which means a low transverse emittance and a high current with a sub-picosecond pulse length, has lots of applications in the accelerator community. The fourth generation light sources are in great demand for the high brightness beams, such as the short wavelength free electron lasers (FELs) [1–6], as well as the inverse-Compton-scattering (ICS) sources for short X-ray pulses [7–12]. For studying novel accelerating techniques such as plasma-based accelerators [13–18] and for the generation of coherent THz radiation [19–23], the ultrashort electron bunches are also required.

On the one hand, short bunches are commonly achieved by magnetic compression. The electron bunch with an energy difference in time is compressed when drifting through a series of dipoles arranged in a chicane configuration. The time-energy correlation along the bunch can be tuned by means of an accelerating section upstream of the chicane. To get a shorter and more longitudinal symmetric beam, a linear time-energy correlation is required, which can be realized by an accelerating structure at a higher harmonic cavity with respect to the main accelerating section [24]. However, to restrain the transverse emittance dilution due to the bunch self-interaction via coherent synchrotron radiation [25], the magnetic compression should be applied at a relatively high energy. For example, in the LCLS injector, the bunch length is compressed by 5 times in the first-stage magnetic compressor at 250 MeV energy [26].

On the other hand, a method termed velocity bunching [27] is able to compress the bunch using the velocity difference introduced by a traveling rf wave at a much lower energy. The compression ability has been shown in the previous experimental works [28–30], and the generation of femtosecond electron bunch with a very low charge has also been proposed and studied [31]. To prevent the transverse emittance dilution, velocity bunching must be integrated into an emittance compensation process [32], which has been proposed in reference [27]. The simultaneous demonstration of the emittance compensation process and velocity bunching has been reported in reference [29] with a compression factor of 3, while the maximum compression factor is above 14 according to the results of measurement.

In order to prevent irreversible emittance growth, the slice envelope oscillations produced by mismatches between the space charge

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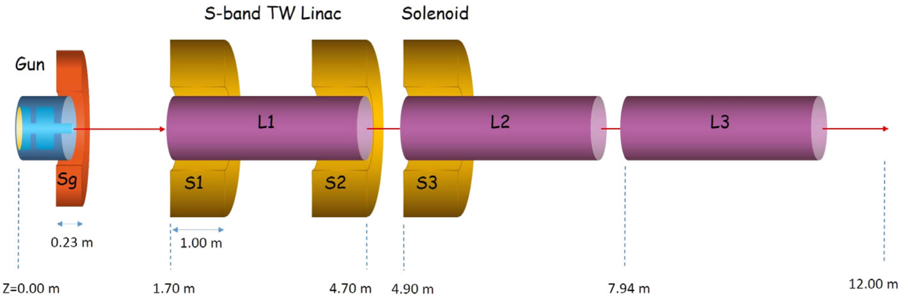

Fig. 1. The photoinjector layout. The S-band rf gun (1.6 cell BNL type gun) with a gun solenoid (Sg) is followed by three TW constant gradient linacs (L1, L2, L3). The first rf cavity is surrounded by two long solenoids (S1, S2) at both ends, and the second rf cavity is embedded in one solenoid (S3) at the entrance.

correlated forces and the external focusing gradient should be kept under control during the velocity bunching process. It has been certified that the long solenoid around the accelerating structure can provide a necessary focusing to make the envelope stay close to an equilibrium mode [29]. As we know that the solenoid lens can be used to compensate the emittance growth caused by the linear forces (i.e. with respect to the position of the particle in the beam) but not the nonlinear one. Therefore, the challenge turns into preserving a symmetric temporal distribution of the beam during the dramatic compression process. It implies that the rf non-linearity should be suppressed as much as possible. L. Serafini and M. Ferrario have also pointed out that the maximum achievable peak current is limited by the rf non-linearity [27].

In the previous experimental study, traveling wave accelerators with a relatively high gradient (20 MV/m) is used [28,29], however, the asymmetric temporal distribution of the compressed bunch is obvious in the measurement and simulation results [28,33]. To preserve the symmetric temporal distribution of the beam, the time-energy correlation in the beam should be as linear as possible during the bunching process. Therefore, the higher order terms of the energy spread introduced by the traveling rf wave should be restrained. To realize the symmetry in the beam, a relatively low gradient linac has been proposed for velocity bunching in the previous work [34]. Based on the prior optimization, a scheme named brake-applied velocity bunching (BAVB) is proposed in this paper. In which, the electron bunch is injected into the accelerator at a deceleration phase, like “a brake is applied”, and gradually slips to an acceleration phase. During the whole compression process in the accelerator, the energy chirp induced by the rf field is mostly linear. Since the bunching process can be regarded as a linear compression, the symmetric temporal distribution of the beam can be maintained, meanwhile the transverse emittance can be compensated by the solenoids. A photoinjector with the layout shown in Fig. 1 is modeled to prove the extreme compression regime with a good compensation of transverse emittance. To obtain a significantly compressed beam with a high transverse brightness, the rf compressor is wrapped by two separate solenoids at both ends, and one-third of the compressor is not embedded in our proposal, because the dramatic and linear compression happens mostly in the uncovered region. According to our simulation study, the peak current of electron bunch can be above 1.8 kA (compression ratio is above 19) with a good emittance compensation by using the BAVB scheme.

2. Principle of the brake-applied velocity bunching

Fig. 2 shows one rf period of electric field in a general traveling wave (TW) structure, the 90° and 0° are defined as the crest and zero crossing of the rf, respectively. The initial beam is injected at a deceleration phase, then it slips back to an acceleration phase since the velocity of the injected beam is slightly slower than the phase velocity of the rf wave. The bunch is compressed during the slippage, and its time-energy correlation is maintained relatively linear. Fig. 2 schematically shows the principle of the proposed BAVB scheme. We would like to present a brief demonstration to realize this mechanism.

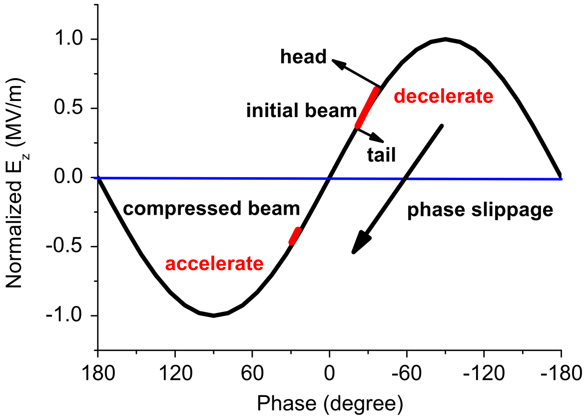

Fig. 2. Principle of the brake-applied velocity bunching.

The velocity bunching mechanism in a TW structure, with a longitudinal electric field $E_z = -E_0 \sin(k_{rf} z - \omega t + \phi_0)$, can be approximately expressed as [34]:

$$\Delta\phi_e = \frac{\sin\phi_0}{\sin\phi_e}\Delta\phi_0 + \frac{1}{2\alpha\gamma_0^2 \sin\phi_e}\Delta\gamma_0, \tag{1}$$

where ϕ_0 and ϕ_e are the injection and exit phase of the reference particle with respect to the rf wave, $\Delta\phi_0$, γ_0, and $\Delta\gamma_0$ are the initial phase length, energy and energy spread respectively, $\Delta\phi_e$ is the phase length after compression. The $\alpha = eE_0/mc^2 k_{rf}$ is the normalized acceleration gradient, k_{rf} is the wave number and $\omega = k_{rf} c$ is the angular frequency. Eq. (1) evaluates the phase compression for a beam with a certain initial phase length and a certain energy spread.

To illustrate the relationship between the injection phase and the output phase after the beam is compressed, we will give a model calculation on a TW cavity with two different accelerating gradients. Assuming a bunch of electrons with 3.8 MeV kinetic energy, 3.8 ps rms bunch length (3.9 degrees in phase length) and 5.4% energy spread, is sent through a TW rf cavity at different injection phases. The nominal parameters above are derived from the beam at the gun exit of the injector, further details of which will be presented in the next section. The model calculation results of the injection and extraction phase length based on Eq. (1) are presented in Fig. 3. The space charge force and solenoid focusing are not considered in the calculation, and the slice energy spread is uncorrelated at different longitudinal locations.

To get the maximum compression factor, a deceleration phase is in demand, furthermore, a TW rf structure with a low gradient should be used. It is notable that too large injection phase which causes an “over compression” should be carefully avoided, because the longitudinal cross-over will induce a phase space “wave breaking” and a transverse emittance growth [35]. In the TW structure with a lower gradient, the bunch can be injected at a higher deceleration phase, which indicates

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