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LONGITUDINAL SHAPING FOR BEAM-DRIVEN PLASMA WAKEFIELD ACCELERATORS

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Abstract

The generation of high quality driven electron beam (high peak current and small beam size) is quite important for the beam-driven plasma accelerator. Besides, a linearly ramped, more exactly, the triangular current distribution is more suitable. In this paper, by adjusting the phase and the amplitude of the harmonic linearizer, the linear ramped current distribution electron beam is generated by the FEL linac. The CSR introduced emittance growth and the jitters of the electron are researched. The electron beam generated by the ramped driven beam in the plasma is researched as well.

INTRODUCTION

The free-electron lasers (FELs) [1] have been recognized as one type of the 4th generation light sources and witnessed an impressive development in the last decade. Nowadays, many x-ray FEL facilities have been built or under-construction around the world. However, limited by the low accelerating gradient (both the normal conducting copper structures and the superconducting structures), the hard x-ray FEL facilities, as well as the high energy colliders, are at large scales with expensive cost. Thus, high gradient electron-beam-based plasma wakefield accelerator (PWFA) [2], especially high transformer ratio (HTR) plasma wakefield accelerator, capable of the compact accelerators, has made great progress recently. In the future development of PWFA, high transformer ratio, meaning the high efficient accelerating gradient, will be one key experimental goal for many plasma wakefield accelerator facilities, such as FACET II at SLAC [3].

For beam-driven PWFA, the high quality driven electron beam with high peak current and small beam size is necessary. In addition, compared with the Gaussian longitudinal current distribution, the linearly ramped, more exactly, the triangle shaped driven bunches are preferred to achieve a high transformer ratio. To drive ideal wakefield in the nonlinear blowout regime, beam peak current of over 5 kA will be needed, which is a tough requirement. However, most of the x-ray FEL facilities based on two-stage compression linac have an exacting requirement for the electron beam, which is quite suitable for the generation of the triangle shaped driven beam. It is convenient to generate the beam by adjusting the parameters of the harmonic linearizer and the bunch compressor chicane to vary the second-order term of the non-linear effects during the compression process.

In this paper, we would like to introduce the scheme to generate the triangle shaped driven bunches on Shanghai soft x-ray free electron laser facility (SXFEL) [4]. The article is organized as follows, the principle of the scheme is introduced in Sec. II. In Sec III, we give the start to end simulation results based on Shanghai soft x-ray FEL facility. Finally, summaries and conclusions are given in Sec. IV.

THEORY

For many scientific fields, including nuclear physics, short-wavelength FELs, beam-driven plasma wakefield accelerators, the requirement of the high peak current demands an extreme compression of the electron beam (about 1 to 2 orders of magnitude), which is easily dominated by the non-linear effects, such as the sinusoidal RF time-curvature and the compressor's second-order momentum compaction terms. A harmonic cavity (HC), usually an X-band, is implemented in the normal conducting linac to compensate the nonlinearity of the chicane and the upstream rf curvature. Theoretical analysis and numerical simulations have been carried out to linearize the compression process [5]. The schematic layout of a typical acceleration and compression systems is shown in Fig. 1 with the symbols defined as voltage (V), RF phase (ϕ) and wavelength (λ) of each accelerator section in the injector (L0) and the linac (L1), as well as the chicane momentum compaction coefficients (R_{56}, T_{566}).

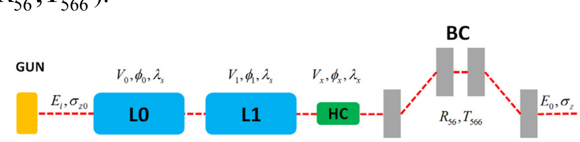

Figure 1: Schematic layout of the gun, the linac segments and the first chicane.

With initial beam energy E_i (at the end of the gun), and after passage through the accelerator RF systems, the electron energy at the first chicane is given as [more details in Ref. 1]

$$E_0 \approx E_i + eV_0\cos(\phi_0 + k_s z_0) + eV_1\cos(\phi_1 + k_s z_0) + eV_x\cos(\phi_x + k_x z_0) \tag{1}$$

where z_0 is the longitudinal position of the electron beam with respect to the reference particle, and

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$k_{s,x} = \dfrac{2\pi}{\lambda_{s,x}}$ are the RF wavenumbers of the S-band and the X-band cavities.

The relative energy deviation to the second-order in bunch length coordinate z_0 can be written as

$$az_0 + bz_0^2 = \frac{\Delta E}{E_0} \approx \left(\frac{-eV_0 k_s \sin\phi_0 - eV_1 k_s \sin\phi_1}{E_0}\right) z_0 + \left(\frac{-eV_0 k_s^2 \cos\phi_0 - eV_1 k_s^2 \cos\phi_1 + eV_x k_x^2}{2E_0}\right) z_0^2 \qquad (2)$$

where the harmonic cavity RF phase is usually set to $\phi_x = \pm\pi$.

When the beam passes through the chicane, the bunch length coordinate z is given as (to the second-order as well)

$$z = z_0 + R_{56} \cdot \frac{\Delta E}{E_0} + T_{566} \cdot \left(\frac{\Delta E}{E_0}\right)^2 \qquad (3)$$

where $T_{566} \approx -\frac{3}{2} R_{56}$ is satisfied for a typical chicane.

Substitute equation (2) into equation (3), one has

$$z = \left(1 + aR_{56}\right) z_0 + \left(bR_{56} + a^2 T_{566}\right) z_0^2 \qquad (4)$$

In order to achieve the higher peak current, the second order term should be set to zero, guaranteeing a linear longitudinal compression. With the linear compression relation $-aR_{56} \approx 1 - \sigma_z / \sigma_{z_0}$, one could finally have the necessary harmonic voltage as

$$eV_x = \frac{E_0\left[1 + \dfrac{\lambda_s^2}{2\pi^2}\dfrac{T_{566}}{\left|R_{56}\right|^3}\left(1 - \dfrac{\sigma_z}{\sigma_{z_0}}\right)^2\right] - E_i}{\left(\dfrac{\lambda_s}{\lambda_x}\right)^2 - 1} \qquad (5)$$

According to equation (5), the second order term of the non-linear effects during the compression process can be well compensated and the approximately symmetric current distribution of the electron beam, such as the Gaussian or the flattop, can be achieved after the chicane. However, for the beam-driven plasma accelerator, a linearly ramped, more exactly, the triangular current distribution is more suitable as the wakes generated by the driven beam is linear. By adjusting the voltage of the harmonic cavity, the second order term of the non-linear effect plays an important role during the compression process, generating the ramped current distribution after the beam passes through the bunch compressor chicane.

NUMERICAL SIMULATIONS

Figure 2: the scheme layout of the injector and the linac of the SXFEL.

The Shanghai Soft x-ray Free Electron Laser (SXFEL) will be the first soft x-ray user facility based on two-stage cascaded HGHG in China. The linac of the SXFEL, as shown in Fig. 2, consists of a 1.6-cell S-band photocathode RF gun, a laser heater system, an X-band harmonic cavity as the linearizer, two bunch compressor chicanes (BC1, BC2) and three main accelerator sections L1 (S-band, accelerate the beam to 250 MeV), L2 (C-band, 630 MeV) and L3 (C-band, 1.5 GeV).

In order to generate the high peak current electron beam as the driven beam for beam-driven plasma wakefield accelerator under the approximate linear compression condition, 3D start-to-end tracking of the electron beam were carried out with the code ASTRA and ELEGANT for the simulations in the injector and the main linac, respectively. In the simulations, a 10 ps flattop laser is injected in the photocathode gun to generate the electron beam with the charge of 1 nC, the peak current of 100 A and the normalized emittance of 1 mm mrad. The electron beam is accelerated to 250 MeV and 630 MeV in the first and second accelerator section (L1, L2) respectively. At the same time, the bunch is compressed to 15 times (to 1.5 kA) and 9 times (to over 10 kA) in the two stage bunch compressor system. Finally, the bunch is accelerated to 1.5 GeV in the last accelerator section (L3). The longitudinal phase space evolution of the electron beam along the linac is shown in Figure 3, in which one can find the electron beam with the bunch length of 100 fs (FWHM), peak current of over 10 kA. The current distribution is approximately Gaussian. The longitudinal energy chirp of the electron beam at the end of the linac comes from the longitudinal wakefield in the accelerator structures.

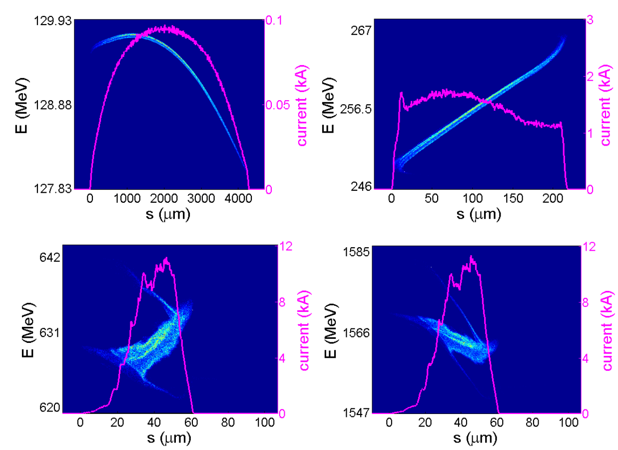

Figure 3: Longitudinal phase space of the electron beam along the beamline at the exit of (top left) the injector; (top right) the BC1; (bottom left) the BC2 and (bottom right) the linac. The bunch head is to the left.

As we described above, it is convenient to vary the current distribution to generate the ramped distribution by adjusting the amplitude of the harmonic cavity. In our simulations, the voltage of the X-band is increased about 4.5%, yielding the asymmetric distribution because of the second-order term according to equation (4). The longitudinal phase space of the electron beam at the end of the BC1 and the linac are shown in Fig. 4. The

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triangular-current-distribution electron beam is achieved at the end of the linac and the peak current is about 10 kA with the bunch length of 130 fs.

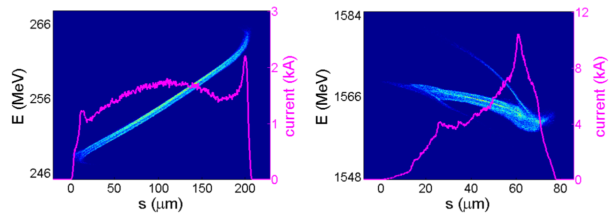

Figure 4: Longitudinal phase space of the ramped electron beam at the exit of (left) the BC1 and (right) the linac.

The requirement of the high peak current demands the extreme compression and very short bunch length. When the electron beam passes through the bunch compressor chicanes, the coherent synchrotron radiation (CSR) can be emitted either by the short bunch or by the longitudinal density modulation on the bunch, which will produce the transverse emittance growth and degrade the quality of the electron beam significantly. In the past several decades, great efforts have been made by a number of researchers to study the effects of CSR on electron beam quality in theory and simulations. In the simulations, the particle tracking code ELEGANT was used, where the method of including CSR effects in drift space following the chicane dipole is developed and implemented. The transverse emittance evolution of the electron beam along the beam line is given in Figure 5. The initial normalized (horizontal and vertical) emittance from the injector is about 1.2 mm mrad. After the beam passes through the two-stage bunch compressor system, the vertical emittance maintains well while the horizontal emittance grows to 5 mm mrad and 7 mm mrad in the two-stage chicanes respectively. The growth of the horizontal emittance brings the difficulties on beam focus downstream of the linac. The transverse beam size of the electron beam at the end of the linac is given in Figure 5 as well, in which one can see that the vertical beam size is about 15 μm while the horizontal beam size is about 45 μm.

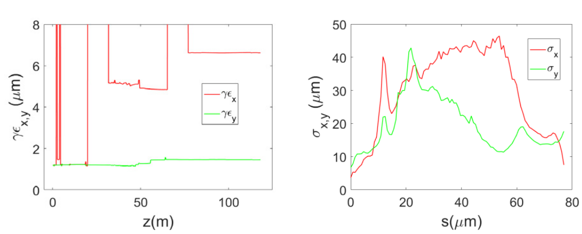

Figure 5: Normalized emittance along the beamline (left) and transverse beamsize along the bunch (right).

As the driven beam, the stability of the electron beam quality have an effect on the generated wake in the plasma, thus the stability of the target beam. The power jitter of the drive laser, the phase error and the voltage error in the linac will affect the stability of the charge, energy, current distribution of the electron beam. The electron beam sensitivity of the linac is investigated by uncorrelated random effects of the SXFEL, as listed in Table 1. With these linac errors in the simulations, Figure 6 summarizes various parameters distribution along the electron bunch for 100 shots of linac output, including the central energy and current distribution.

Table 1: Main Errors in the Simulations.

Charge error (rms, %)	2
Timing jitter of drive laser (rms, fs)	200
Phase error of the S-band (rms, deg.)	0.05
Voltage error of the S-band (rms, %)	0.05
Phase error of the C-band (rms, deg.)	0.08
Voltage error of the C-band (rms, %)	0.08
Phase error of the X-band (rms, deg.)	0.1
Voltage error of the X-band (rms, %)	0.1

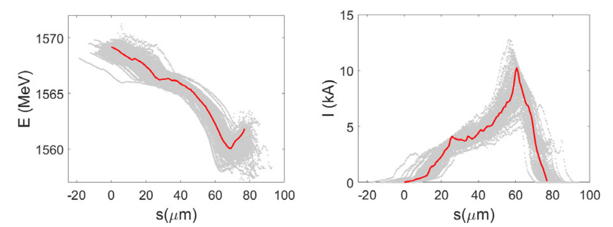

Figure 6: Shot-to-shot jitters of various electron beam parameters: central energy (left), current (right).

Based on the electron beam parameters described above, we preformed 3D-PIC simulations using QuickPIC to study HTR PWFA. The results are shown in Figure 7, from which one can find that an approximate 4 transformer ratio is achieved.

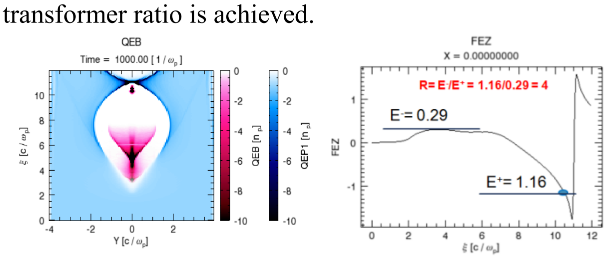

Figure 7: QuickPIC results with the triangle shaped driven bunches.

CONCLUSIONS

In this paper, by adjusting the phase and the amplitude of the harmonic linearizer, the linear ramped current distribution electron beam is generated by the FEL linac as the driven beam for the high transformer ratio plasma wakefield accelerators (PWFA). The CSR introduced emittance growth and the jitters of the electron are researched. The start-to-end simulation results show that an approximate 4 transformer ratio could be achieved

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