TWIN BUNCHES AT THE FACET-II

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Abstract

Twin electron bunches, generated, accelerated and compressed in the same acceleration bucket, have attracted a lot of interest in the free-electron lasers and wakefield acceleration. The recent successful experiment at the LCLS used twin bunches to generate two-color two x-ray pulses with tunable time delay and energy separation. In this note, we apply the twin bunches to the plasma wakefield acceleration. Numerical simulations show that based on the beamline of the FACET-II, we can generate high-intensity two electron bunches with time delay from ~100 fs to picoseconds, which will benefit the control of high-gradient witness bunch acceleration in a plasma.

INTRODUCTION

The recent development of two-color x-ray free-electron lasers (XFELs), as well as the successful demonstration of high-gradient wakefield acceleration in a plasma, have attracted strong interest in electron trains, where two or more electron bunches are generated, accelerated and compressed in the same radio-frequency period. The twin bunches have been used at the Linac Coherent Light Source (LCLS) [1] to generate two-color two x-ray pulses with tunable time delay and energy separation [2]. The longitudinal dynamics and control of the twin bunches in the LCLS have been analyzed in Ref. [3]. With respect to the standard single-bunch two-color methods [4–6], the twin-bunch technique allows to reach saturation for each bunch and hence improves the FEL output by over 1 order of magnitude.

Besides generating two-color XFELs, the twin-bunch scheme can be also applied to the beam-driven plasma acceleration, e.g. the two-bunch experiment at the FACET [7, 8]. Compared with the masking technique [7], the twin-bunch method will have greater flexibility in control of the charge distribution, peak current, time delay and energy separation of the two bunches.

In this note, we study the application of the twin-bunch technique to the FACET-II. Numerical simulations show that we can generate high-intensity (~ 10 kA) two bunches with time delay from ~100 fs to picoseconds. We also find that wakefields in the beamline are very strong to increase the time delay and induce a large remaining energy chirp on the beam.

DESCRIPTION OF THE TWIN-BUNCH METHOD

The twin-bunch method is schematically illustrated in Fig. 1. In a typical high-energy linear accelerator with double chicane systems, such as the LCLS and FACET-II, the electrons are generated by a photocathode illuminated by a train of two laser pulses with a variable delay on the order of a few picoseconds. The twin bunches are accelerated off-crest in the linear accelerators and compressed by the two chicanes to increase the peak current. Energy difference between the two bunches will be generated due to off-crest acceleration and wakefields. With energy difference, dispersion sections will affect their arriving time and vary the time separation between them. The parameters of the beamline, including the initial delay of the two laser pulses, bunch charge and current, phases of each linac section and R_{56} of the two chicanes, will all have effects on the final status of the two bunches. Through optimization of the whole system, we can generate two bunches with desired peak current, time delay and energy separation.

The longitudinal beam dynamics of the twin-bunch method have been discussed in Ref. [3] with wakefield effects. The final time delay of the two bunches can be written as

$$\Delta T = -\frac{\tau_0}{C} + \frac{2r_e LN}{\gamma a^2}\left(\frac{1}{\eta} - 1\right) R_{56} \tag{1}$$

where τ_0 is the initial time delay, η is the filling factor of the two bunches, N is the particle number and C is the total compression ratio. L/a^2 denotes the wakefeld amplitude and R_{56} is the longitudinal dispersion of the second chicane. The detailed definitions of the these variables can be seen in Ref. [3]. The first term on the right side of Eq. (1), called compression term, means the compression of the initial time delay. The second term is the effects of wakefield. Based on this equation, we can vary the time delay by changing the wakefield effects.

TWIN BUNCHES FOR FACET-II

The twin bunches at the FACET-II are used to study the beam-driven plasma wakefield acceleration. The required parameters of the electron beam are different from those in the LCLS. Some beamline parameters have been shown in Fig. 1. These numbers are fixed in the following simulations. The charge at the FACET-II is 1 nC for each bunch and the peak current needs to be around 10 kA, which are both much larger than the ones in the LCLS. So the wakefield effects are much stronger at the FACET-II.

In this note, we use *LiTrack* [9] to study the dynamics of the twin bunches. *LiTrack* is a 1D simulation code, which only tracks the longitudinal phase space. The transverse beam dynamics and collective effects except the longitudinal wakefields are fully neglected. The simulation starts at the beginning of L1 and ends at the end of L3. In the simulations, we vary the initial beam distribution, the phases of L1 and L2,

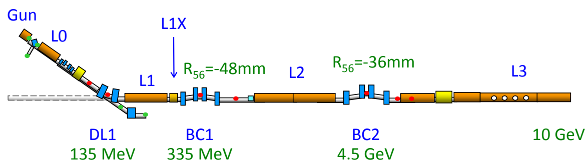

Figure 1: A schematic layout of the twin-bunch method in a double-chicane beamline (not to scale).

and the maximum energy gain of the 4th-harmonic cavity L1X. The parameters used in the simulation are give in Table. 1.

Table 1: Beamline Parameters of the FACET-II for the Twin-bunch Generation

Parameter	**Value**	**Unit**
Fixed parameters		
Total charge Q	2	nC
Energy after injector E_0	135	MeV
Energy at BC1 E_1	335	MeV
Energy at BC2 E_2	4.5	GeV
Energy after L3 E_3	10	GeV
BC1 R_{56}	-48	mm
BC2 $R-56$	-36	mm
L1X phase ϕ_X	-180	degX
Scanned parameters		
Initial time delay τ_0	6~10	ps
L1 phase ϕ_1	-10~-25	degS
L2 phase ϕ_2	-25~-50	degS
L1X energy gain E_X	0~25	MeV

The longitudinal profile of the electron beam after injector is assumed to be parabolic, which is consistent with the measurements in the experiment [10]. The initial longitudinal phase space at the entrance of the L1 is given in Fig. 2 with time separation 6 ps. The head bunch lies to the left with $z < 0$. For a given time separation, we also need to optimize the bunch length of single bunch to control the filling factor η, which can vary the wakefield effects as shown in Eq. 1.

From the scan results, we pick out “working points" with required peak current. We define the final time delay and energy separation as the difference of the average arriving time and energy of the two bunches, respectively. If we require the peak current of core part for FACET-II larger than 10 kA, the available distribution of time delay and energy separation is shown in Fig. 3.

The available time delay ranges from ~100 fs to 1 ps. And the energy separation is from 1.6% to 2.9%. The area around the time delay of ~500 fs has the most counts of “working points". It seems that there is a correlation between the time delay and energy separation along the area. Large time delay mostly corresponds to large energy separation. In Fig. 4, we show some typical examples of phase spaces with time delay from ~100 fs to more than 800 fs. It can be seen from

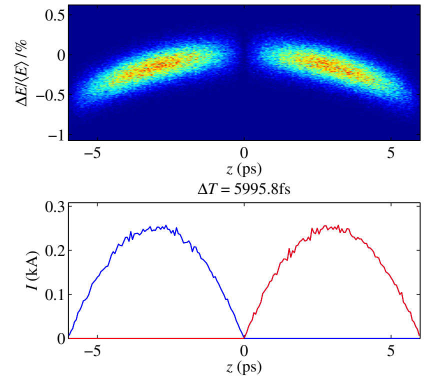

Figure 2: The initial longitudinal phase space of the two bunches at the beginning of L1. The initial time separation is 6 ps. The blue line is for the head bunch and the red ones is for the tail.

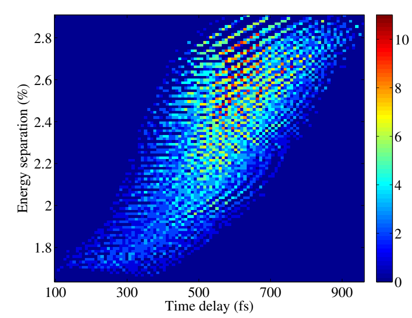

Figure 3: The distribution of time delay and energy separation of the two bunches with peak current of core part >10 kA in the simulation scans. The initial time delay of the two bunches is 6 ps.

these phase spaces that the two bunches have exchanged their order compared with Fig. 2. The tail bunch (high-energy bunch) comes first due to the over compression in BC2. It is also noticeable that there is a negative remaining energy chirp on the phase space of single bunch, which comes from the over compression scheme and strong wakefield-induce energy chirp in L3.

Figs. 5, 6 and 7 show the correlations between the scanned parameters of the beamline and the time delay and energy separation of the two bunches, respectively. The color bar in each figure denotes the energy separation. These figures provide the setting directions of L1/L2 phase and L1X energy gain to generate the required two bunches. For L1/L2 phase, larger off-crest phase gives smaller time delay and energy separation. As for L1X, smaller energy gain corresponds to larger time delay and energy separation.

In the above simulations, the initial delay of the two bunches is 6 ps and the peak current is ~250 A, which is several times larger than the normal injection working condition. However, we can compress the electron beam by velocity bunching in the injector to obtain the required longitudinal profile.

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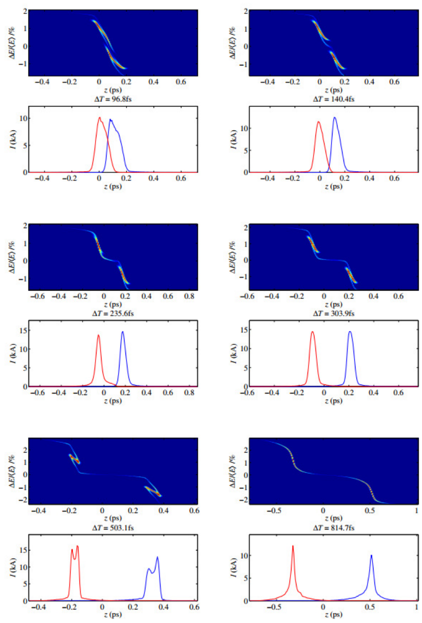

Figure 4: Phase spaces with different time delays from ∼100 fs to ∼800 fs. The initial delay is 6 ps.

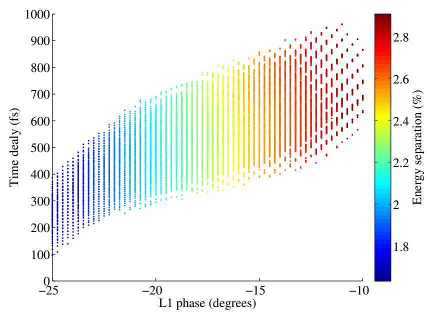

Figure 5: Correlations between the L1 phase and the time delay and energy separation. The initial delay is 6 ps.

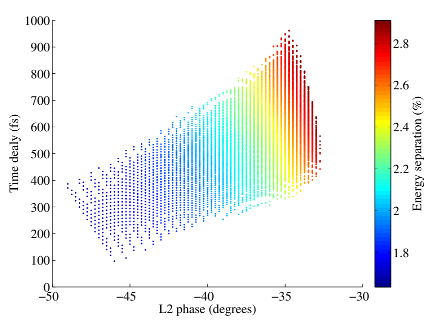

Figure 6: Correlations between the L2 phase and the time delay and energy separation. The initial delay is 6 ps.

If we keep the same filling factor and stretch the beam to larger initial delays, for example 10 ps, the peak current will be reduced to 150 A, which is more reasonable for the injector. With this initial distribution, we can also obtain similar time and energy distribution with Fig. 3 but the range of the time delay is from 400 fs to 1.4 ps, as shown in Fig. 8.

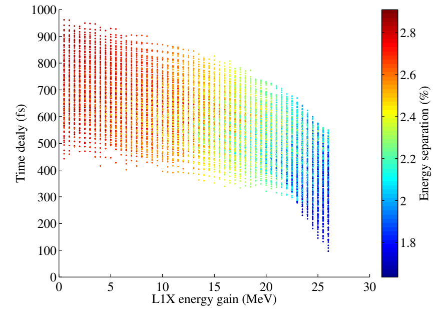

Figure 7: Correlations between L1X energy gain and the time delay and energy separation. The initial delay is 6 ps.

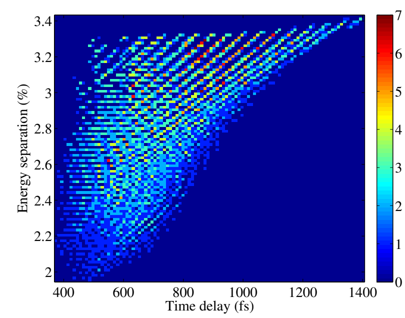

Figure 8: The distribution of time delay and energy separation with peak current of core part >10 kA. The initial time delay of the two bunches is 10 ps.

SUMMARY

In this note, we studied the application of the twin bunches at the FACET-II. Numerical simulations show that based on the beamline of the FACET-II, we can generate high-intensity (∼10 kA) two electron bunches with time delay from ∼100 fs to picosecond level. Due to the large charge and high peak current, the wakefields are very strong to increase the time delay and induce a large remaining energy chirp on the beam. The advantage of this method is its flexibility to control the parameters of twin bunches. The initial longitudinal profile, bunch charge and current, off-crest acceleration phase, R_{56} and energy of chicanes and the settings of the high-harmonics cavity are all effective knobs to vary the compression of the two bunches. In this note, we only presented preliminary results and have not optimized all knobs. More simulations can be done based on some specific requirements for the two bunches. Start-to-end simulations are also necessary to include more considerations.

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