9th International Particle Accelerator Conference IPAC2018, Vancouver, BC, Canada JACoW Publishing
ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAK131

INVESTIGATION OF TWO-BUNCH TRAIN COMPRESSION BY VELOCITY BUNCHING

Dan Wang[†], Hongze Zhang, Xiaolu Su, Qili Tian, Xing Liu, Lixin Yan[#], Yingchao Du, Wenhui Huang, Chuanxiang Tang
Department of Engineering Physics, Tsinghua University, 100084 Beijing, China

Abstract

Two electron beamlets, also referred as two-bunch train with adjustable time and energy spacing are popular in many applications such as two color FEL and pump-probe experiments. We investigate compression of two-bunch train via velocity bunching scheme in a traveling wave accelerator (TWA) tube by varying the phase of TWA tube in a very large range. Beam dynamics simulations show that when the phase injected into the accelerator tube for the beam is set to $\ll -100^0$, velocity bunching occurs in a deep over-compression mode, where two-bunch train is continuously tunable in time and in energy space, and the emittance of each sub-bunch is also preserved. In the experiment, we use energy spectrum and defecting cavity to diagnose the train's energy space and time space respectively, the measurements demonstrated that two-bunch train through deep over-compression scheme is separated both in time and in energy space, which also agree well with the predictions.

INTRODUCTION

The generation of two spaced electron bunches (two-bunch train) has been the subject of intense investigation in the recent past due to their application to diverse fields such as free-electron lasers (FELs) and beam-driven plasma wakefield acceleration (PWFA). In an X-ray free-electron laser, two-bunch train are used to generate two-color X-ray pulses with large output power for time-resolved X-ray pump/X-ray probe experiments. They can also find applications in staged seeded FELs to reduce the spectral noise and the temporal jitter. Furthermore, the application of this concept to witness-bunch plasma wakefield acceleration, allows for greater flexibility in controlling the charge distribution, peak current, and time delay, which can improve the performance of the PWFA [1-2].

The longitudinal dynamics or compression of the two-bunch train has been discussed in Ref. [2-4], both with 4-dipole chicane and with velocity bunching scheme. Reaching picosecond delays is crucial for the time resolved investigation of nuclear motion in X-ray excited samples. However, the control of twin bunches is coupled with the compression of each individual bunch. So the final longitudinal separation of the twin bunches is limited under the requirement for high beam quality such as peak current, emittance, etc.

In the velocity bunching (VB) scheme, the compression takes place in rectilinear trajectory, free from coherent synchrotron radiation emission, which is the primary cause of emittance degradation in magnetic compressors. The VB scheme is usually associated with emittance compensation for low energy beam, in which the beam's emittance growth is optimized by tuning the long solenoids surrounding the accelerating section, thus maintaining the high brightness beams from photoinjectors for FEL or other advanced accelerations in PWFA [5].

Bunch train compression by VB scheme has been studied in Ref. [6-7]. And Ref. [7] has put up an optimized compression scheme for bunch train compression, which is called the deep over-compression mode. In deep over-compression mode, the phase injected into the accelerator tube for the bunch train is set to $\ll -100^0$, reversing the phase space and maintaining a velocity difference within the injected beam, thereby giving rise to a compressed electron bunch train after a few-meter-long drift segment.

Here we experimentally investigate compression of two-bunch train via velocity bunching scheme in a traveling wave accelerator (TWA) tube, varying the phase of TWA tube in a very large range, coving the phase of deep over-compression mode where phase $\ll -100^0$, and measure the beam's energy space and time space with energy spectrum and defecting cavity respectively. The measurements demonstrated that two-bunch train through deep over-compression scheme is separated both in time and in energy space, which agree well with the predictions.

BEAM DYNAMICS SIMULATION

Beamline Parameter

We study the velocity bunching scheme with the beamline at Tsinghua University acceleratory laboratory, which is a normal setup for photo injector as shown in Fig.1. A 3 meter S-band SLAC type travelling wave accelerating (TWA) is placed around 1.5 meter after a BNL/KEK/SHI type 1.6 cell S-band photocathode rf gun. There is a defecting cavity after 5 meters drift segment downstream the TWA tube, and we set this position as a target to the compressed beam in the simulations.

Two-bunch electron train can be generated with two-bunch laser train illuminating on the copper photocathode.

[†] wangdan16@mail.tsinghua.edu.cn
[#] yanlx@mail.tsinghua.edu.cn

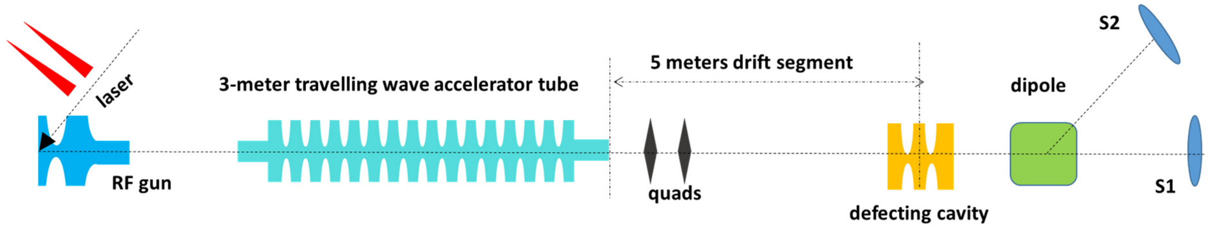


Figure 1: Beamline setup at Tsinghua University.

And the laser train is produced via direct UV laser pulse stacking using birefringent α-BBO crystal. The charge of each sub-bunch is 100 pC and the initial bunch interval is 8 ps in the simulations. The gradient of the RF gun is set to 110 to 120 MV/m, to boost the beam to relativistic energy in a short distance and reduce smearing effect due to space charge. And the TWA tube further accelerate the beam to ~50 MeV without compression.

Compression of Two-Bunch Train with TWA Tube

We study the two-bunch compression mainly by varying the TWA tube phase, in a relatively large range from -180 degree to 0 degree. 0 degree is the maximum acceleration phase without any compression. The velocity bunching scheme for bunch train compression has been studied in Ref [5] before, but with smaller tuning range of TWA tube phase of [-100 ~ -80] degree. It is evident that this method suffers from a smearing effect from longitudinal space charge forces, which causes the initial modulation to be blurred and tend to disappear for high beam currents. And also even in the over-compression mode where TWA phase is close to -100 degree, the distance tween sub-bunches are limited to ~ 1 ps. Here we further vary the compression phase to <<-100 degree, where velocity bunching occurs in a deep over-compression mode as studied in Ref [6], and trends to be an optimized working mode as theory predicted.

Astra code [8] is performed to simulate the beam dynamics with space charge effect. The phase space distribution of two-bunch train with different TWA phase at target position is shown in Fig.2. Both energy and time distributions are shown under different phase. We partially repeat the results reported in [] when the compression phase is around -80 degree, which is a full-compression mode of the two bunch, thus two bunch merged together in time space as shown in the right-top image of Fig.2. When we further decreased the TWA phase to <<-100 degree, velocity bunching occurs in a deep over-compression mode as studied in Ref [], where two-bunch train is adjustable in a relatively large range in both time and energy space. Furthermore, the main benefit of this scheme are the relatively large phase acceptance and the uniformity of compression for the bunch train. As the typical image shown in the middle and bottom line in Fig.2, when the TWA phase is tuned from -120 degree to -170 degree, two-bunch train is still separated both in time and energy space.

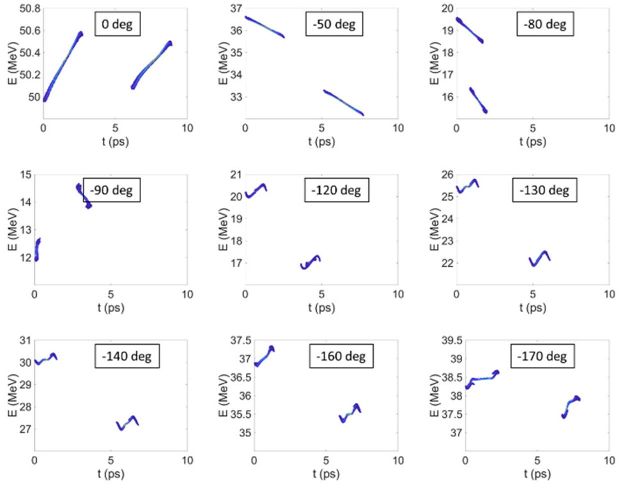


Figure 2: Phase space distribution of two-bunch train with different TWA phase.

Figure 3 shows the static parameters versus the TWA phase. Including (a) beam energy of each sub-bunch, (b) emittance of each sub-bunch, (c) rms. bunch length of each sub-bunch and (d) bunch interval between sub-bunches. The initial interval and all intervals in the under-compression mode have positive values indicating that bunch 1 is in front of bunch 2, whereas negative values indicate the reverse case, with bunch 2 in front. The two regions of zero values in the bunch interval curves correspond to the merged case. Here the space charge effect on the bunch interval is slight, mainly because the charge of each sub-bunch is not very high (100 pC) and the interval between the bunches is relatively large (a few picoseconds).

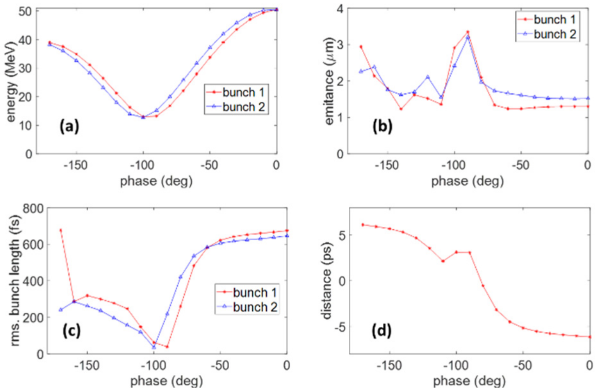


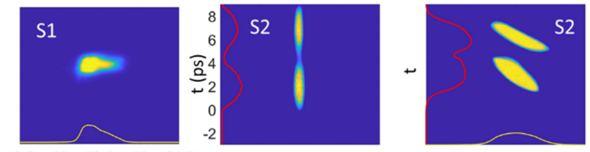
Figure 3: Parameters versus the TWA phase. (a) beam energy of each sub-bunch, (b) emittance of each sub-bunch, (c) rms. bunch length of each sub-bunch and (d) bunch interval between sub-bunches.

We focus on the deep over-compression regions where phase varies from $-170°$ to $-110°$, we find that the time spacing between two sub-bunches are continuously adjustable over a large range up to 6 ps. Meanwhile the emittance and rms. bunch length of each sub-bunch is relatively low, thus maintaining high quality beams for advanced applications. Those results indicate the optimization of the two-bunch train under the deep over-compression scheme.

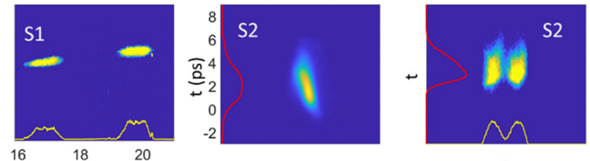
EXPERIMENTAL MEASUREMENT

We experimentally investigate compression of two-bunch train via velocity bunching scheme with beamline setup as shown in Figure 1. Energy spectrum (dipole magnet with YAG screen S1) and defecting cavity with YAG screen S2 are used to diagnose the train's energy space and time space respectively.

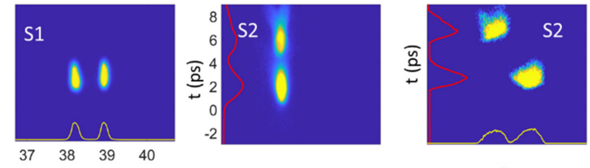
Measurement results of three different phases are shown in Fig.4. Left column shown the energy space when dipole magnet is on and deflecting cavity is off. Middle column show time space distribution when deflecting cavity is on and the dipole is off. While the right column shown results on screen S2 when dipole magnet and deflecting cavity are both slightly on. We have calibrated the energy spectrum with different current of the dipole magnet, as well as the defecting cavity with different RF power, thus the left and middle column are shown in absolute value. The right column haven't been calibrated but has the ability to show the energy separation and time separation.



(a) phase = 0 deg



(b) phase = -90 deg



(c) phase = -170 deg

Figure 4: Measured energy space and time space of two-bunch train with different TWA phases.

Figure 4 shows that: (a) the energy separation is minimal and the time spacing is about 5 ps at target position when phase=0 degree, which is the maximum acceleration case. (b) The energy separation is about 3 MeV and the time space is merged or can't be separated due to the limit resolution of the deflecting cavity when phase=-90 degree, which is around full compression case. (c) When phase=-170 degree, deep over-compression mode, there is about 1 MeV in energy spacing and about 5 ps in time spacing. The measurement indicate that the energy space and time space are both separated for two sub-bunches as theory of deep over-compression mode predict.

CONCLUSION

We investigate compression of two-bunch train via velocity bunching scheme in a traveling wave accelerator (TWA) tube by varying the phase of TWA tube in a very large range. Beam dynamics simulations show that when the phase injected into the accelerator tube for the beam is set to $\ll -100^0$, velocity bunching occurs in a deep over-compression mode, where two-bunch train is continuously tunable in time and in energy space, and the emittance of each sub-bunch is also preserved. Energy spectrum and defecting cavity are used to diagnose the train's energy space and time space respectively, and the measurements demonstrated that two-bunch train through deep over-compression scheme is separated both in time and in energy space, which also agree well with the predictions. Such two-bunch train with adjustable time and energy spacing will find applications in such as two color FEL and pump-probe experiments.

REFERENCES

[1] A. Lutman *et al.*, "Experimental demonstration of femtosecond two-color x-ray free-electron lasers," *Physical review letters*, 2013, 110, 134801.

[2] Z. Zhang *et al.*, "Longitudinal dynamics of twin electron bunches in the linac coherent light source", *Physical Review Accelerators and Beams*, 2015, 18, 030702.

[3] Z. Zhang *et al.*, "Flexible pulse delay control up to picosecond for high-intensity twin electron bunches", *Physical Review Accelerators and Beams*, 2015, 18, 090701.

[4] C. Ronsivalle *et al.*, "Large-bandwidth two-color free-electron laser driven by a comb-like electron beam," *New Journal of Physics*, 2014, 16, 033018.

[5] L. Serafini and M. Ferrario, "Velocity bunching in photo-injectors," in American Institute of Physics Conference Series, 2001, 581, pp. 87–106.

[6] D. Wang *et al.*, "Theoretical analysis and simulation study of the deep overcompression mode of velocity bunching for a comblike electron bunch train", *Physical Review Accelerators and Beams*, 2018, 21, 024403.

[7] M. Ferrario *et al.*, "Experimental demonstration of emittance compensation with velocity bunching," *Physical review letters*, 2010, 104, 054801.

[8] ASTRA, `http://www.desy.de/~mpyflo/`