ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-MOPTY015

BEAM COMPRESSION DYNAMICS AND ASSOCIATED MEASUREMENT METHODS IN SUPERCONDUCTING THz SOURCE

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Abstract

To ensure the quality of high brightness electron beams needed by the terahertz FEL facility at China academy of engineering physics(CAEP),which aims to obtain 100 to 300 terahertz light, a feed-back control system is required to monitor the amplitude and phase jittering by measuring beam arrival time as well as bunch length at the site of the beam position monitor(BPM).

In this paper, we make an idealized model of injector section and deduce analytic expressions of bunch arrival time and bunch length. In consideration of the space charge effect on bunch lengthening, bunch arrival time and bunch length as a function of DC gun voltage, buncher field amplitude and buncher phase is carefully calibrated by means of particle in cell (PIC) simulation. With the time and space resolution of the BPM, the control accuracy of phase is estimated to be 0.01 degree, while the amplitude is 0.04%.

INTRODUCTION

Owing to the challenge of advanced accelerator applications, the control accuracy of amplitude and phase is becoming stricter for control systems, under which circumstance emerges methods of beam-based feed-back control. Two representative examples are the fast feedback installed in Stanford Linear Collider(SLC) using BPM readings and fitted beams parameters to stabilize beams [1]; while a combination of RF and beam based feedback loops used at The Free Electron LASer at Hamburg(FLASH) has achieved regulation of ~10fs rms bunch arrival time jitter [2].

For the THz-FEL facility at CAEP [3], the main goal for the accelerator control systems is to achieve highly precise regulation of relative amplitude and absolute phase jitter below 0.01 % (rms) and 0.01 degrees (rms).

KINEMATIC MODEL WITHOUT SPACE CHARGE

In THz-FEL, the electron bunch has a length of ~30ps at the exit of the DC gun, and needs a bunching process through the downstream buncher to reach ~10ps length before entering the superconducting accelerating cavity. The BPM located close to the entrance of the accelerating cavity is used for beam position measurement. Here an ideal kinematic model without space charge is utilized to deduce analytical expressions of bunch arrival time and bunch length (compression ratio) at the site of BPM.

Arrival Time Jitter

In the FEL facility, the arrival time of electron bunch at the site of downstream BPM is effected by several factors, such as the voltage of the photocathode DC electron gun, the electric field amplitude of the buncher and working phase of the bucnher. When DC voltage, buncher amplitude and phase have a small perturbation, the consequent arrival time jitter can be decided by means of perturbation. As the perturbation of above mentioned factors is quite small compared to the set value, means of perturbation is used to find the linear relation between the arrival time and perturbation. Given parameters of the FEL facility, the linear relation between arrival time jitter and above-mentioned factors in shown by Equ. (1) to Equ. (3).

$$\Delta t\,(ps) = -0.78\Delta V_0(kV)\ . \tag{1}$$

$$\Delta t\,(ps) = -3.6\Delta\phi(deg)\ . \tag{2}$$

$$\Delta t\,(ps) = 0\cdot\Delta V_b(kV)\ . \tag{3}$$

Here, V_0 is DC gun voltage, φ is the phase of the buncher, V_b is the gap voltage of buncher.

A Space Charge Tracking Algorithm (ASTRA) code is used to simulate the arrival time jitter versus DC gun voltage and phase of the buncher to check validity of the kinematic model. The result is shown in Fig. 1 ,Fig. 2 and Table 1.

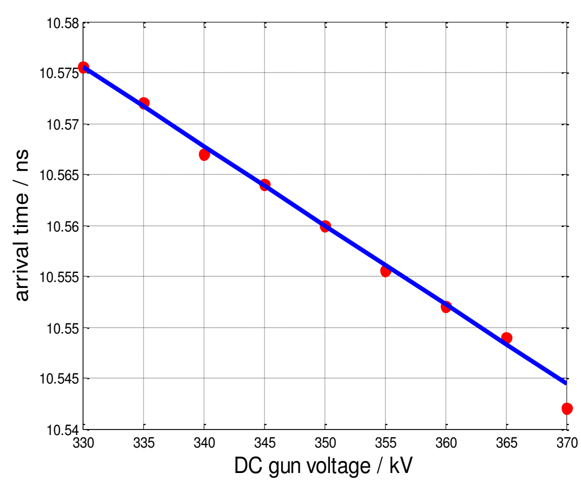

Figure 1: arrival time vs DC gun voltage.

Here, the red dot is the result of ASTRA simulation, while the blue line is theoretical result obtained from Equ. (1), and the same setting is used in following figures.

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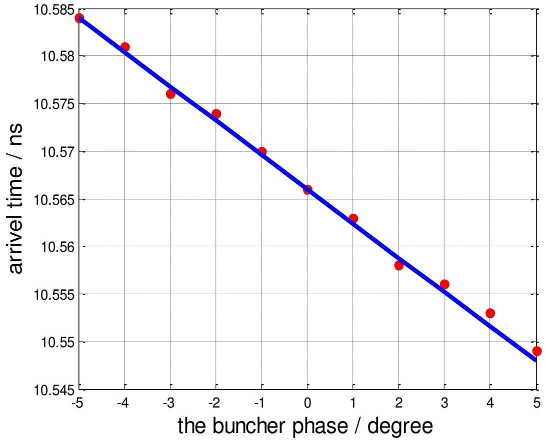

Figure 2: arrival time vs buncher phase.

From Fig. 1, Fig. 2 we can see that the relation between arrival time jitter and DC voltage or buncher phase fits quite well with the theoretical line.

Since working on 0 degree, when the electric field amplitude changes while the phase remains, the average energy of electron bunches do not change, thus having no effect on bunch arrival time, which is the essence of Equ. (3).

Table 1: Arrival Time vs Electric Field Amplitude

E(MV/m)	0.8	0.9	1.0
t/ns	10.566	10.566	10.566

Conclusion can be drawn from Table 1 that field amplitude of the buncher has no influence on beam arrival time just as Equ. (3) implies. As the simulation result presented above, the ideal kinematic model without space charge is expectedly in agreement with ASTRA simulation result, which illustrates validity of the model and assumptions within.

PIC SIMULATION

Because of the low accelerating gradient of the DC gun(~350 kV), the electron beam is far from relativistic when exiting DC gun, therefore the space charge effect is such a dominating factor of bunch lengthening that it must be taken into consideration. There is hardly no way can we obtain the analytic expression of arrival time and compression ratio with space charge. However, getting scaling law of arrival time and compression ratio versus DC gun voltage, buncher's amplitude and phase by means of dynamic simulation can be of great help to beam-based feedback control.

Just as simulation without space charge, ASTRA code is used to calculate arrival time jitter when DC gun voltage, buncher amplitude and phase vary in a small range, of which the result is given by Fig. 3 and Fig. 4.

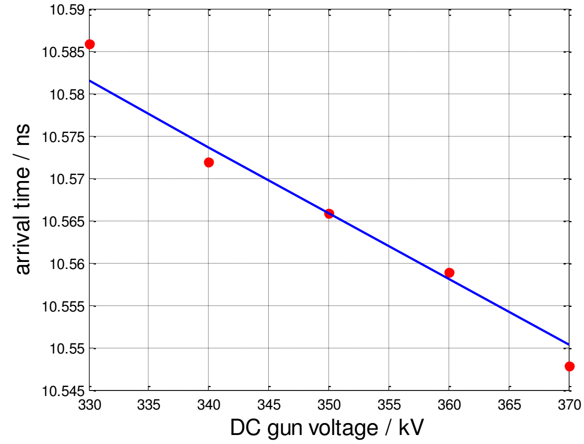

Figure 3: arrival time versus DC voltage.

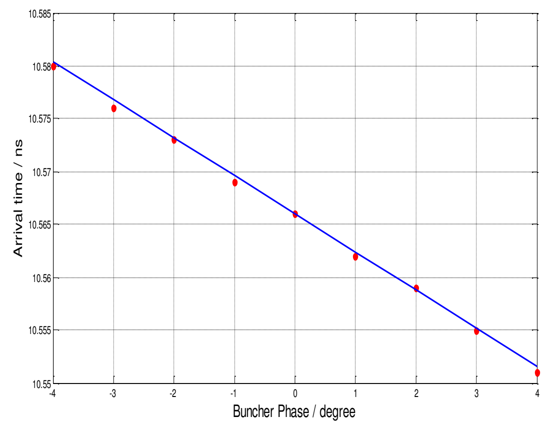

Figure 4: arrival time versus buncher phase.

In Fig. 3 and Fig. 4, the simulation result fit well with the theoretical one, and there is no evident difference when compared to results without space charge in Fig. 1 and Fig. 2. Also, arrival time seems to remain unchanged when the electric field amplitude changes only. Therefore, conclusion can be drawn that space charge has almost no effect on bunch arrival time, which can be explained by the essence of space charge force as internal force.

Though space charge effect has no impact on bunch arrival time, it changes bunch length or compression ratio dramatically because of low energy and high charge of the electron bunch. ASTRA simulation shows that the bunch length has elongated from about 10 ps at the cathode to about 30 ps at the entrance of accelerating cavity. Dynamic simulation from start to end is employed to find scaling law of bunch length versus DC voltage, electric field amplitude and phase of the buncher, which is of practical help to establish negative feedback loops in order to stabilize the electron beams.

With ASTRA code utilized, it's found that bunch length varies linearly with the jitter of DC voltage, electric field amplitude and phase of the buncher, the slope of which is calculated by means of least square fitting. Finally, the scaling law is carefully calibrated, as shown in Table 2. The parameters used here are the same with previous simulation without space charge.

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Table 2: Scaling Law of Bunch Length

factor	jitter	Length jitter
DC voltage	1%	1.785%
amplitude	1%	3%
phase	1°	0.7%

BPM MEASUREMENT

Besides used to monitor beam position, Beam Position Monitor can also be used to measure bunch length using the electron beam spectrum analysis technique [4]. The principle is using two different frequency components of the frequency spectrum of a bunch signal picked up by BPM. The bunch length can be obtained from amplitude ratio of the two frequency components [4]:

$$\sigma = \sqrt{\frac{2}{\Delta\omega^2} \ln\left\{\frac{|F_1(\omega_1)|}{|F_2(\omega_2)|}\right\}} . \quad (4)$$

Here, ω_1 and ω_2 are the chosen two frequencies, F_1 and F_2 are amplitude of the spectrum, and $\Delta\omega^2=\omega_2^2-\omega_1^2$.

BPM can also be used to measure beam arrival time: select one of the high order harmonics and compare it to a reference signal. After filtering and ADC sampling, the phase detector will tell phase difference of the two signals. With the frequency of reference signal used, the phase difference is translated to arrival time jitter:

Precision of Amplitude Control

Since amplitude has no influence on bunch arrival time, it can only be control by measurement of bunch length. Assume a Gaussian bunch, its frequency spectrum is:

$$F(\omega) = q \cdot e^{-\frac{(\sigma\omega)^2}{2}} . \quad (5)$$

From Equ. (5) can we get the relation of precision of spectrum amplitude measurement and bunch length measurement:

$$\left|\frac{\delta\sigma}{\sigma}\right| = \frac{1}{\sigma^2\omega^2}\frac{\delta F}{F} . \quad (6)$$

We can come to an obvious conclusion from Equ. (6) that the resolution of bunch length is proportional to spectrum amplitude resolution, and inversely proportional to bunch length. Provided that the spectrum amplitude resolution of digital circuit is 0.01%, two frequency components are 500 MHz and 4.5 GHz, the bunch length is about 10 ps, then the bunch length resolution is:

$$\left|\frac{\delta\sigma}{\sigma}\right| = \frac{1 \times 0.01\%}{(2\pi \times 0.0045 \times 10)^2} \approx 0.125\% \cdot \quad (7)$$

From Table 2, the buncher amplitude varies 1%, the bunch length varies 3%. According to Equ. (7), the limitation of distinguishing amplitude variation is about 0.04%, i.e. the precision of amplitude control is 0.04%.

Precision of Phase Control

Buncher phase has impact on both arrival time and bunch length, however, bunch length is not sensitive to phase. If the same method used as amplitude control, the precision will not be better 0.2 degree, which is far from satisfactory. Therefore high precision control of phase has to be achieved by arrival time measurement. Suppose the digital phase detector has a resolution of 0.01 degree at 4.5 GHz, the arrival time measurement resolution will be 6 fs. Using result from ASTRA simulation-1degree phase jitter leads to 3.6ps arrival time jitter-when the buncher phase has a jitter of 0.01 degree, arrival time jitter will be 36fs, which can be easily detected by BPM. Therefore, the precision of phase control can reach 0.01 degree.

CONCLUSION

Dynamics study and simulation is made to calibrate arrival time jitter and bunch length variation with DC gun voltage, buncher amplitude and phase jittering. Using BPM to measure arrival time and bunch length simultaneously, 0.01° phase control precision and 0.04% amplitude control precision is obtained, which is of great significance to beam-based feedback systems in THz-FEL facility.

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