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SIMULATIONS OF SIMULTANEOUS MEASUREMENT OF GHz BUNCHES USING A FAST KICKER*

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Abstract

A method of using a fast kicker to measure different bunches in bunch trains simultaneously is proposed in this paper. By using a fast-rising edge power supply, the kicker can give different electron bunches different kick angles, allowing different bunches to be detected on the screen simultaneously. This paper presents measurement methods for the transverse distribution, energy spread, longitudinal phase space, and emittance, along with corresponding simulation results.

INTRODUCTION

Electron bunch trains are currently in high demand in many accelerator facilities, such as inverse compton scattering (ICS) sources [1, 2], high energy computed tomography accelerators [3], free electron laser (FEL) facilities, and the SSMB light source. First proof-of-principle steady-state microbunching (SSMB) experiment proved that SSMB has the potential to produce high average power short wavelength light [4]. Tsinghua University has proposed a conceptual design for the future SSMB accelerator light source [5]. A bunch train with an average current of 1 A is required in the electron injector for the future SSMB light source with a bunch spacing of 350 ps [6]. Diagnostic techniques for bunch trains are therefore also very important. In this paper, we proposed using a fast kicker for bunch train diagnostics. A fast kicker system includes a stripline kicker and a power supply with a fast rising edge. The bunches can be kicked with different strengths because of the ramped deflecting voltage in the kicker. The requirements of the stripline kicker and power supply will be discussed. The beamline design for measuring transverse distribution, energy spread, longitudinal phase space, and emittance will be introduced. The simulation results of a bunch train with 8 bunches spaced at 350 ps (2856 MHz) are presented.

FAST KICKER

Tsinghua University has developed several types of stripline kicker, a typical stripline kicker is shown in Fig. 1 [7]. Transverse electromagnetic (TEM) modes will be excited by connecting electrodes to power supply. When the transmission direction of the pulse power source is in the opposite direction of the particle velocity, relativistic electrons are deflected under approximately equal electric forces and magnetic forces due to the electromagnetic relation of the Poynting vector. The kick angle can be approximately calculated by the following equation:

$$\begin{aligned} \tan(\theta) &= \frac{e}{p\cdot\beta c}\int_0^L |E_x| + |v\cdot B_y| dz \\ &= \frac{2e|E_x|L}{p\cdot\beta c} \\ &= \frac{2e}{p\cdot\beta c}\frac{L}{d}\frac{\partial V}{\partial t} \end{aligned} \quad (1)$$

where e is the elementary charge, L is the effective length, d is the distance between the two electrodes, V is the potential difference between the two electrodes, p is the beam momentum, β is the Lorentz beta, c is the speed of light.

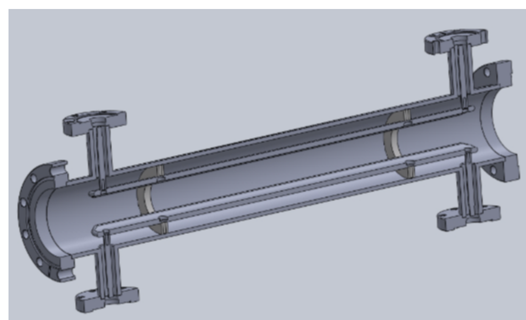

Figure 1: Cross-sectional view of a typical stripline kicker.

In the preliminary design, $L = 0.6$ m, $d = 15$ mm, and the beam momentum in the following simulation is about 46.3 MeV/c. When $\partial V/\partial t = 2$ kV/ns, according to Eq. (1), the kick angle difference between neighboring bunches is approximately 1.2 mrad. The kick angle difference can be modified by adjusting $\partial V/\partial t$, making it adaptable.

SIMULATIONS OF MULTI-BUNCH MEASUREMENTS

The following simulations use only the first eight bunches from the SSMB injector's first accelerating tube, as described in Ref. [6]. Eight bunches have same beam parameters except average energies which are different due to beam loading. OCELOT is utilized in the following simulations and considers the space charge effect [8]. The initial transverse and longitudinal phase space are shown in Fig. 2. Since no asymmetric components are used, the vertical phase space is the same as the horizontal phase space.

Transverse Distribution

Transverse distributions can be easily measured by kicking the bunches in either direction. The beamline design is

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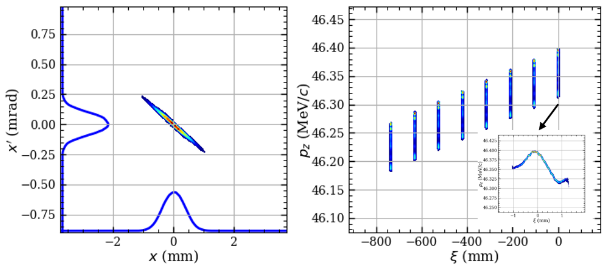

Figure 2: Phase space of the initial bunch train.

shown in Fig. 3, just a kicker and a screen. The kicker kicks bunches vertically, as shown in the vertical phase space in Fig. 4, different bunches get different kick angles. After drifting, the bunches will separate vertically. The position of the screen is chosen at the beam waist to decrease the kick angle. The maximum kick angle in the simulation is 0.6 mrad. The beam distribution on screen is shown in Fig. 4, it can be clearly measured.

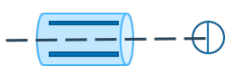
Figure 3: Beamline of transverse bunch profile measurement.

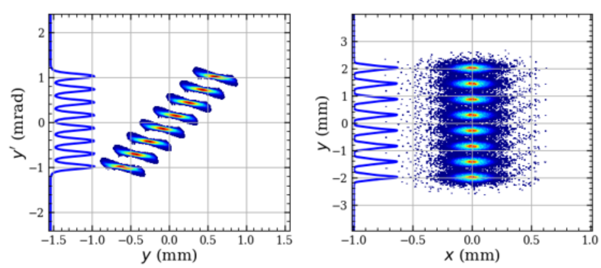

Figure 4: Vertical phase space after kicker (left) and transverse distribution on the screen (right).

If you want to measure the beam transverse distribution at other locations, the position of the screen needs to be changed, and the kick angle needs to be larger to ensure that the bunches are completely separated. This imposes more stringent requirements on the power supply, as well as specific demands regarding the size of the beam pipeline and the screen.

Energy Spread

Using the dispersion properties of the dipole, the energy spread of each bunch in the bunch train can be measured. The beamline schematic is shown in Fig. 5, the deflection directions of the dipole and the kicker are orthogonal. The dipole deflects horizontally and the kicker deflects vertically. The lattice design should be optimized to ensure that the beam's horizontal distribution on the screen primarily reflects the energy spread of the beam, with minimal influence from the initial horizontal beam size and divergence. In the simulation, a dipole with a 1-meter radius and a 30° deflection angle was utilized, with a distance of 1 meter between the dipole exit and the screen. The maximum kick angle is also 0.6 mrad.

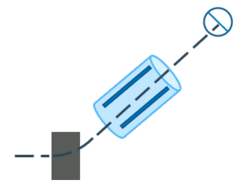
Figure 5: Beamline of energy spread measurement.

The beam profile on the screen is shown in Fig. 6. Not only the mean energy difference between different bunches can be measured, but also the energy spread of each bunch. In fact, kicking the bunches that far is unnecessary if the primary goal is to quantify the mean energy differential between different bunches; simply measuring the slope will suffice.

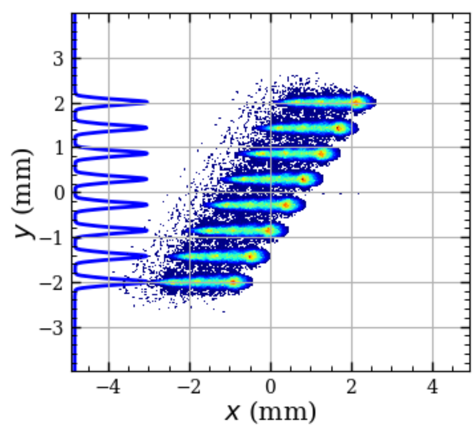

Figure 6: Beam distribution on the screen (energy spread measurement).

Longitudinal Phase Space

The longitudinal phase space measurement of a single bunch requires the combination of a transverse deflection cavity (TDS) and a dipole. The same energy resolution can be obtained by placing a TDS in front of the energy spread measurement beamline, while the time resolution depends on the voltage and frequency of the TDS. A S-band (2856 MHz) TDS is used in the simulation. The schematic of the beamline configure is shown in Fig. 7.

The deflection direction of the TDS is the same as that of the kicker. The TDS deflects electrons at various longitudinal positions within each bunch to achieve time resolution inside the bunch, whereas the kicker kicks bunches at different longitudinal positions within the bunch train to obtain time resolution across the entire bunch train.

The beam distribution on the screen is shown in Fig. 8. The longitudinal phase spaces of eight bunches can be clearly

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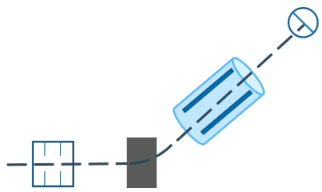

Figure 7: Beamline of longitudinal phase space measurement.

observed. The reconstructed longitudinal phase space on the screen has a structure similar to Fig. 2, but due to the limited time and energy resolution, the distribution is smeared on the screen.

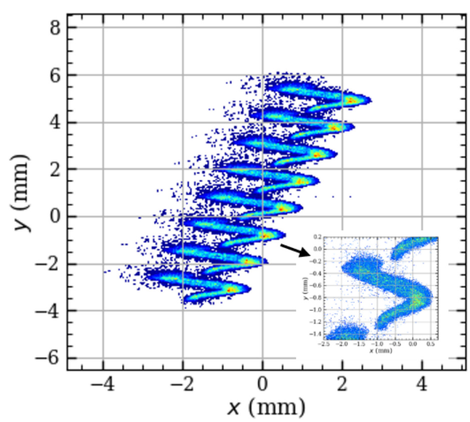

Figure 8: Beam distribution on the screen (longitudinal phase space measurement).

Transverse Emittance

The quadrupole scan method is employed here for the emittance measurement. For different quadrupole strengths, different transfer matrix can be obtained, and different beam sizes can be measured on screen. By changing the quadrupole strength and measuring the beam size several times, Eq. (2) can be established;

$$\sigma^{i}_{11} = R^{i\,2}_{11}\sigma_{11} + 2R^{i}_{11}R^{i}_{12}\sigma_{12} + R^{i\,2}_{12}\sigma_{22} \qquad (2)$$

where i represents the i-th measurement, R_{11} and R_{12} are elements in the transfer matrix. By solving Eq. (2), σ_{11}, σ_{12} and σ_{22} can be obtained, and the emittance is $\epsilon = \sqrt{\sigma_{11}\sigma_{22} - \sigma_{12}^2}$. Different bunches can be separated by adding a kicker after the quadrupole, allowing their distributions and emittances to be measured and calculated simultaneously. The emittance measurement beamline is shown in Fig. 9.

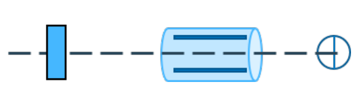

Figure 9: Beamline of emittance measurement.

In theory, Eq. (2) can be solved with only three measurements. However, in practice, several measurements and the least-squares fitting approach are typically used to reach the solution.

As shown in Fig. 10, by fitting the square of the beam spot size on the screen with the scanned strength of the quadrupole, the corresponding emittance can be calculated. The initial horizontal and vertical emittance are both about 0.267 mm·mrad. The calculated horizontal emittance from the simulation is 0.270 mm·mrad, and each bunch is roughly the same. But the vertical emittance is a little different, the emittance of the first and last bunch are about 0.284 mm·mrad, and that of the two middle bunches is 0.273 mm·mrad. The further the electron beam is deflected, the bigger the measured vertical emittance. This is because the kicker deflects the electron beam in the vertical direction, and the kicker is a dispersion component. In addition, due to the length of the bunch is not zero and the kick voltage rises over time, the deflection angles of electrons at different positions within the same bunch are slightly different.

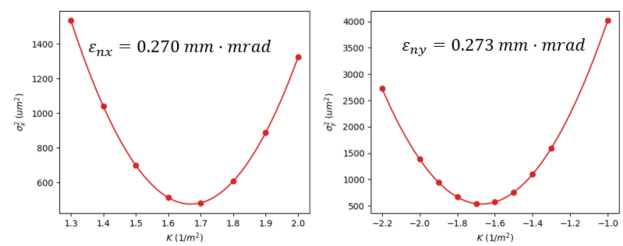

Figure 10: Simulation results of quadrupole scan emittance measurement.

CONCLUSION

A method of measuring GHz bunches is proposed in this paper. Different bunches can be measured simultaneously by using a fast kicker, and simulation results of different measurements are presented. This paper only puts forward a basic concept. Many practical situations such as the jitter of the power supply have not been considered in the simulation. In future experiments, the lattice design should be re-optimized for different beamlines and beam conditions, and there are also different requirements for the power supply and kicker.

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