ULTRASHORT BUNCH TRAIN LONGITUDINAL DIAGNOSTICS USING RF DEFLECTING STRUCTURE*

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Abstract

Ultrashort electron bunch train has been produced using UV laser stacking in Tsinghua University. With an S-band deflecting cavity inserted into the Tsinghua Thomson Scattering beamline, it is possible to characterize the bunch train longitudinal property. This paper briefly introduced the measurement layout in our lab and reported the recent experiment results, including bunch train profile measurement and longitudinal phase space. The main sources of error are also discussed.

INTRODUCTION

The main purpose of the Tsinghua Thomson Scattering X-ray (TTX) beamline is to generate high-brightness electron bunches with small emittance, low energy spread, and high peak currents for the tuneable, ultrashort pulsed x-ray.

Ultrashort electron bunch train has been produced by UV laser stacking in Tsinghua. It could be used for the longitudinal shaping of the bunch to reduce the emittance and to produce the THZ radiation [1]. Time-resolved measurements of the bunch parameter are very important in order to understand and improve the performance.

RF deflecting cavity has been proven to be a powerful tool for the time-resolved characterization of the beam phase space. A 3-cell S-band standing-wave deflecting cavity has been developed and used for the bunch length measurement [2].

In the first section, we briefly review the principle of sliced bunch parameter diagnostics using RF deflecting cavity. In the second section, the measurement layout is introduced. The comparison between the simulation and measurement result is presented in the third section and source of error are also discussed.

SLICED BUNCH PARAMETER CHARACTERIZATION

RF deflecting structure could be considered as an ultrafast oscilloscope. It could be used to generate a phase dependent transverse kick. The phase of deflecting cavity is chosen to give a null kick at the center of the bunch, while the head and the tail will be deflected in the opposite position. After drifting some distance, it will result in a correlation between the longitudinal position and transverse displacement, thus converting the longitudinal information to the transverse. The mechanism is shown in Figure 1.

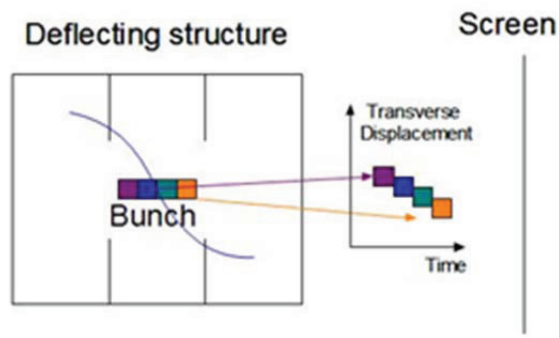

Figure 1: The time resolved bunch measurement using RF deflecting structure.

Since the bunch always has a non-zero emittance, the bunch betatron motion has to be carefully considered in order to improve the resolution.

Longitudinal Resolution

After the deflecting cavity, the transverse motion of the particles can be regarded as the superposition of the natural betatron and the transverse motion due to the phase-dependent kick. Assume the transverse kick is in the y-direction, the motion can be given by [3]:

$$y(s) = y_\beta(s) + y_{kick}(s) \quad (1)$$

And the transverse motion due to the kick is given by:

$$y_{kick}(s) = \frac{eV_0}{pc}\sqrt{\beta_d\beta_s}\sin\Delta\varphi\sin\theta \quad (2)$$

where β_s is the beta function in position s, β_d is the beta function in the deflector ,$\Delta\Phi$ is betatron phase advance from the deflector to the screen ann d θ is the RF phase when the particle enters the deflector. When θ is a small angle, there is a linear correlation between the transverse displacement and longitudinal position. Thus the total vertical rms bunch size on the screen s=z can be written as:

$$\sigma_y^2 = \sigma_{y\beta}^2 + S_z^2\sigma_\theta^2, \quad (3)$$

with $S_z = \frac{eV_0}{pc}\sqrt{\beta_d\beta_z}\sin\Delta\varphi$ and $\sigma_{y\beta}$ is the natural beam size on the screen when the RF cavity is switched off .

Longitudinal resolution is defined when the second term of the rms bunch size due to the RF deflector equals to the natural beam size, which gives:

$$\sigma_t = \frac{\sigma_\theta}{\omega_{RF}} = \frac{\sigma_{y\beta}}{S_z\omega_{RF}} = \frac{\sqrt{\epsilon_{nor}\gamma}}{\sqrt{\beta_d}\sin\Delta\varphi eV_0} \quad (4)$$

where ε_{nor} is the transverse normalized emittance of the bunch, γ is the Lorentz factor of the beam and V_0 is the deflecting voltage of the RF cavity.

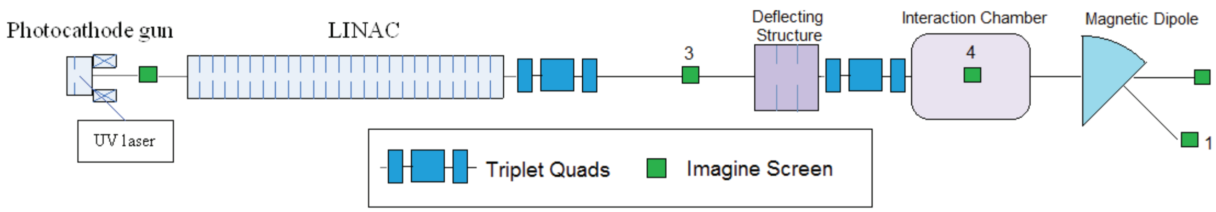

Figure 2: Layout of the TTX bunch diagnostics facility.

MEASUREMENT SETUP

The ultrashort bunch train diagnostics was performed in the TTX beamline. The layout of the experiment is shown in Figure 2. The maximum accelerating gradient on the cathode is 65MV/m, the photon injecting phase is 20 degree. An S-band traveling wave linac accelerated the bunch to 47MeV. Several YAG screens is inserted in the beamline for beam diagnostics

Bunch Train Profile

The bunch train is vertically streaked by the deflecting structure. The Triplet Quads is applied to adjust the accelerating optics to enhance the resolution. In case of bunch train profile diagnostics, YAG screen 2 is used to record the beam image. The deflecting structure could be adjusted to as high as 1MeV.

Longitudinal Phase Space

By adding a dispersing dipole between the deflecting structure and the screen, one can characterize the longitudinal phase space of the bunch.

The dipole employed in our experiment has a radius of 50 cm and a design bending angle of 45 degrees. In this case, YAG screen 1 is applied to take the bunch image. The screen is located at a distance of 32 cm from the dipole. In order to have enough resolution on the screen, both the vertical and horizontal beam size has to be minimized by adjusting the triplet strength.

Slice Energy Spread imposed by the deflector

Another systematic error of the longitudinal phase space diagnostics comes from the deflecting cavity. As the bunch passes through the deflecting structure, additional energy spread is induced. This is well described by the Panofsky-Wenzel theorem. When the beam Lorentz factor γ is much greater than 1, the formula can be written as:

$$V_y = \frac{j}{k}\frac{\partial V_z}{\partial y}, \tag{5}$$

where V_y is the deflecting voltage ,k is the RF wave number and $\frac{\partial V_z}{\partial y}$ is the derivative of longitudinal accelerating voltage, which is the source of the induced slice spread. Note that there is a 90 degree phase difference, thus the induced slice energy spread reaches its maximum when the deflecting voltage it experienced is zero. That is exactly the case when the deflector is used for bunch diagnostics, where the phase of the deflector is set to make the bunch centre a null transverse kick. In our experiment, the effect of energy spread has been taken into account by performing measurements at different deflecting voltage.

MEASUREMENT RESULT AT TTX

Time Resolved Profile Of Bunch Train

Several beam profile measurements have been done for bunch trains with different numbers of sub-bunches. Figure 3 shows the 4-bunch train profile measurement result, comparing with PARMELA simulation. In this case, the FWHM of each UV laser sub pulse is 1.1ps. The injecting interval between the sub pulses is 2.4ps. The total charge of the bunch train is about 1pC. And to get time-resolved information, calibration is required by measuring the beam vertical position with respect to the RF phase. And RF phase is adjusted by the phase-shifter.

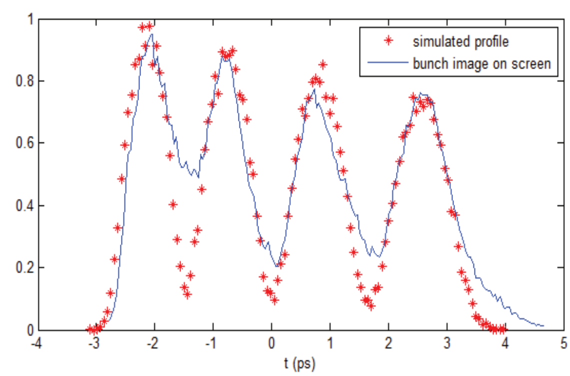

Figure 3: Longitudinal profile of 1pc 4-bunch train.

Although initially the laser pulses and the intervals between them are the same, at the deflector location, the sub-bunches profile and their intervals have small difference, mainly because the compressing factor is different in the photo-injector.

The 8-bunch train diagnostics has shown that 8-pulse laser injection could produce the bunch train containing 7 peaks inside the bunch train profile, when the bunch charge is adjusted about 30pC. This is also verified by the PARMELA code. Figure 4 shows the 7-peak bunch profile. This bunch might have advantages for the THZ radiation production by CTR mechanism. Further investigation is underway to better understand and control the bunch.

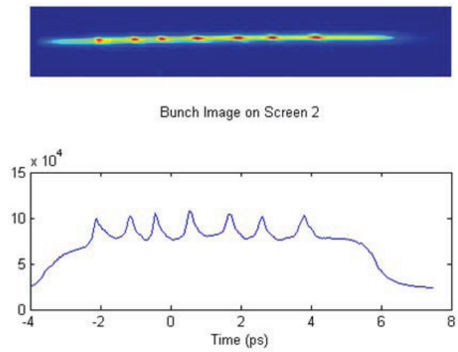

Figure 4: 7-peak bunch train produced by 8 pulse laser injection.

Bunch Train Longitudinal Phase Space

Figure 5 shows the 4-bunch train longitudinal phase space measurement result on screen 1, comparing with the simulated longitudinal phase space by PARMELA.

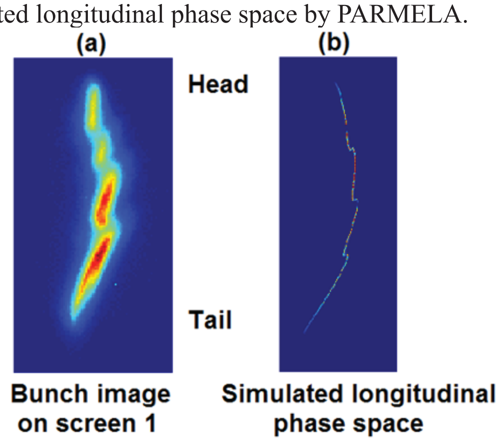

Figure 5: Longitudinal phase space of 15pc 4-bunch train.

The bunch charge is about 15pC. We could clearly see that the bunch train centre was accelerated on crest, thus gained the maximum energy, about 47.3MeV, while the tail and head gained lower. There are four sub-bunches in the bunch and in each sub-bunch there is energy chirp due to the space charge effect. However, the slice energy spread shown on the screen has an average value of 35keV, which is much bigger than the simulated longitudinal phase space by PARMELA, which is about 1 keV. Thus the value 35keV is the estimation of the energy resolution of this experiment setup.

There are mainly two factors making the discrepancy, the natural beam size due to the betatron motion, and induced energy spread by the RF deflector. By applying equation (5), the induced energy spread could be given as:

$$\sigma_{\mathrm{Ei}} = \mathrm{k}V_y \sigma_{yd} = \mathrm{k}V_y \sqrt{\beta_d \epsilon_y} \tag{6}$$

where σ_{yd} is the vertical rms beam size inside the deflector .The total slice energy spread image on the screen is the superposition of the betatron motion and horizontal motion due to the slice energy spread. The relation can be described as:

$$\sigma_{\mathrm{x}}^2 = \sigma_{\mathrm{x}\beta}^2 + {\sigma_{\mathrm{xi}}}^2 + {\sigma_{\mathrm{xE}}}^2 \tag{7}$$

where $\sigma_{\mathrm{x}\beta}$ is the natural betatron beam size, σ_{xE} and σ_{xi} is beam size due to the natural slice energy spread and induced slice energy spread.

An experiment is made to investigating this effect by measuring the slice energy spread with respect to RF kick strength.

The experiment result is shown in Figure 6.

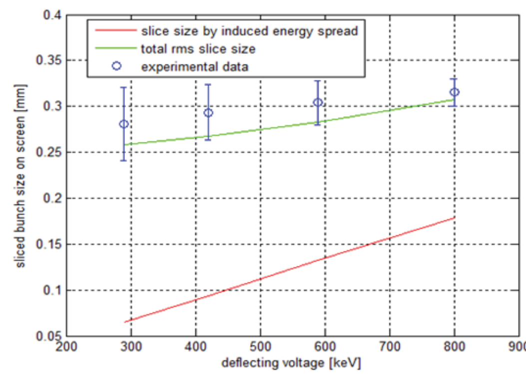

Figure 6: Slice beam size with respect to the kick strength (deflecting voltage).

The red line in the figure shows the theoretical bunch slice size on screen due to the induced energy spread versus the kick strength, while the green line indicates total theoretical size of slice energy spread image, which is observed on the screen. The experiment shows that the bunch image of the slice energy spread will increase as kick strength increases. If the slice energy spread is on the order of induced energy spread, this relation could be used to calculate the natural slice energy spread.

CONCLUSION

Ultrashort bunch train longitudinal diagnostics has been performed in the TTX beamline using the RF deflector. Bunch train profile and longitudinal phase space was measured. The RF Deflecting cavity will impose slice energy spread on the beam, which limits the energy resolution. Further improvement is still underway by upgrading the triplet power source to better control the beam optics.

REFERENCES

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[3] Paul Emma, Josef Frisch, “A Transverse RF Deflecting Structure for Bunch Length and Phase Space Diagnostics”, Proceedings of PAC 2001