LONGITUDINAL BEAM DIAGNOSTICS WITH A STREAK CAMERA AT THE TAIWAN PHOTON SOURCE

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Abstract

The Taiwan Photon Source (TPS) streak camera system has been used for longitudinal beam studies since the early commissioning stage. This paper first presents a representative high-current instability observation associated with the CU15 insertion device taper and then recent measurements of bunch length and synchronous phase under operation with the superconducting RF (SRF) + passive 3rd harmonic cavity (HC), here abbreviated as SRF HC. The CU15 case shows different instability behaviors along the fill pattern in streak images. The SRF HC measurements provide bunch-by-bunch information under different fill patterns and SRF HC settings for comparison of bunch lengthening and phase shift. Under operation with the passive SRF HC, a phase drift of about 35 ps is observed along the bunch train, consistent with transient beam loading under quasi-uniform filling. These measurements show that the streak camera is useful for longitudinal diagnostics and machine studies at the TPS.

INTRODUCTION

The Taiwan Photon Source (TPS), located at the National Synchrotron Radiation Research Center in Hsinchu, Taiwan, is a 3 GeV low-emittance synchrotron light source. Under high-current operation and different fill patterns, longitudinal beam measurements are important for storage ring studies and machine tuning. A streak camera system was introduced at the TPS during the early stage of facility development [1]. Subsequent work included early bunch length measurements and longitudinal instability observations at the TPS diagnostic beamline (BL40) [2], ultrashort bunch measurements in low-alpha operation [3], and investigations of impedance effects under single-bunch conditions [4]. Streak-camera-based longitudinal diagnostics and bunch profile studies have also been reported at other storage rings and synchrotron light sources [11–14]. Longitudinal instability phenomena under high-current operation have also been reported [5, 6]. As background, Liu *et al.* reported instability in operation at the TPS with a superconducting RF (SRF) + passive 3rd harmonic cavity (HC), here abbreviated as SRF HC [7–9]. This paper presents first a representative high-current observation associated with the CU15 insertion device taper, and then recent streak camera measurements of bunch length and synchronous phase under SRF HC operation.

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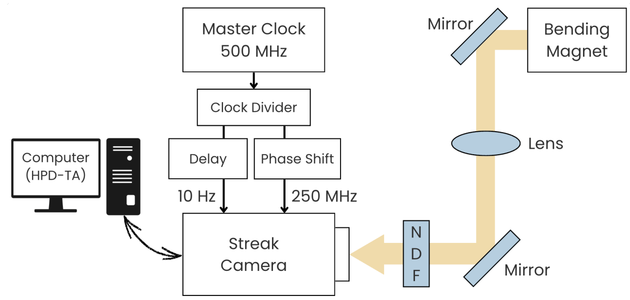

Figure 1: Block diagram of the streak camera measurement system.

STREAK CAMERA SYSTEM AT THE TPS

The TPS streak camera system is installed at the synchrotron radiation diagnostic beamline for measurements of the longitudinal time structure of electron bunches in the storage ring. The block diagram of the streak camera measurement system is shown in Fig. 1. The main instrument is a dual-sweep streak camera, C10910 from Hamamatsu Photonics [10], equipped with one fast-sweep unit, one slow-sweep unit, and two synchroscan sweep frequencies (125 MHz/250 MHz) for temporal and transverse measurements. The system receives visible light signals emitted from a bending magnet and, after optical transport and focusing, delivers the light to the streak camera, where the temporal distribution is converted into a spatial image. The present measurement modes include synchroscan and dual-sweep operation. The synchroscan mode is used mainly for high-time-resolution measurements of a single bunch and provides bunch length and longitudinal profile information. The streak camera temporal resolution is about 1 ps, as verified with a femtosecond laser source. The dual-sweep mode preserves both fast-sweep and slow-sweep information simultaneously, and is therefore suitable for observing relative multi-bunch behavior over a period of time. In the present measurements, the dual-sweep mode was used to compare relative bunch phase positions, and to observe unstable motion under multi-bunch filling conditions.

LONGITUDINAL BEAM STUDIES

CU15 Taper High Current Observation

In 2019, during TPS operation at 500 mA, a deformation of the vacuum chamber taper in the CU15 insertion device at BL19A formed a cavity-like structure, increasing the local impedance and parasitic heat load. Under this condition, the streak camera images provided qualitative evidence of multi-bunch longitudinal instability. As shown in Fig. 2, the bunches in the leading part (a) of the train remained

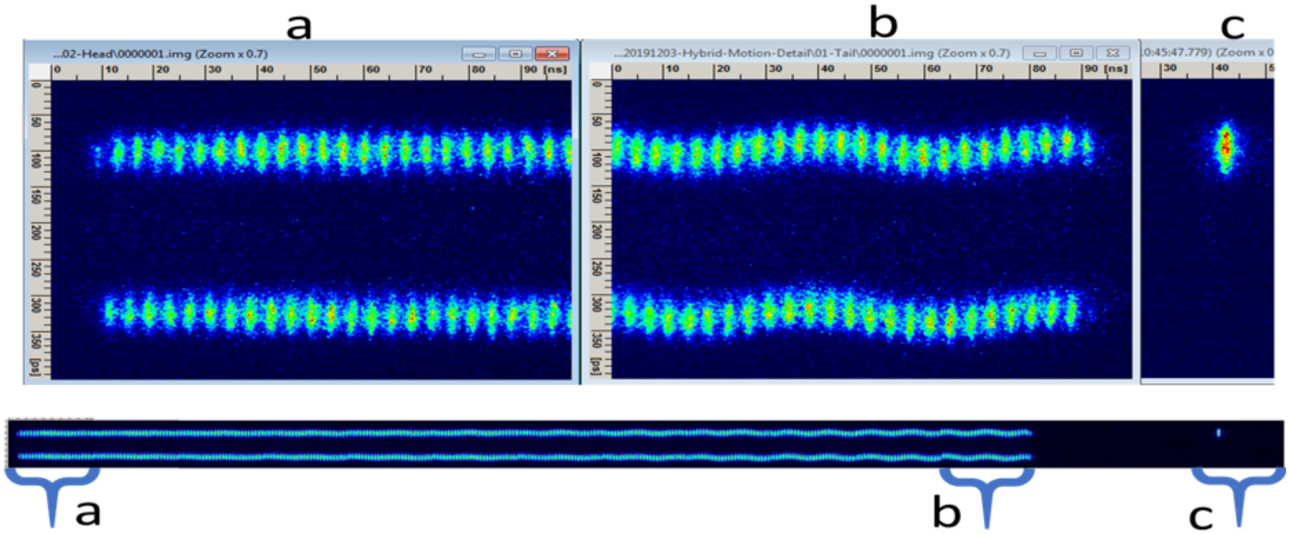

Figure 2: Streak camera image of the CU15 high-current case, with enlarged regions showing stable and unstable bunch patterns.

stable in longitudinal position, whereas wave-like oscillation trajectories appeared near the end of the multi-bunch-filled section (b), suggesting longitudinal coupled-bunch motion. The isolated single-bunch region (c) did not exhibit the same level of oscillation. Further investigation used GdfidL electromagnetic simulations [15] of the deformed taper geometry to obtain the longitudinal impedance spectrum. Using the simulated impedance in the coupled-bunch instability analysis [6], the largest growth rate was predicted for mode number 327. However, modal analysis of the measured data identified instabilities at mode numbers 396 and 398, as shown in Fig. 3. The oscillation envelopes in the time domain, depicted in Fig. 3(a), show bunch-dependent longitudinal oscillation patterns observed over a 40 ms window. Correspondingly, Fig. 3(b) presents the evolution of the modal spectrum, identifying the dominance of these specific modes. The discrepancy between the predicted and measured unstable mode numbers may be attributed to differences between the deformation geometry used in the simulation and the actual chamber deformation. The issue was later mitigated by replacing and redesigning the transition taper to remove the cavity-like geometry, followed by additional cooling improvements to the CU15 system [6]. After these modifications, 500 mA operation became thermally stable, and the associated longitudinal instability was no longer observed.

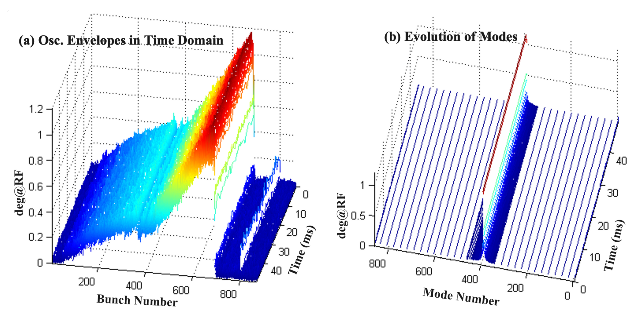

Figure 3: Experimental analysis of longitudinal multi-bunch instability during 500 mA operation in the CU15 taper: (a) Time-domain oscillation envelopes across different bunch numbers over a 40 ms observation window; (b) evolution of the modal spectrum.

Bunch Length Measurements on SRF HC Test

Measuring the bunch length is one of the main applications of the TPS streak camera system. Earlier studies included bunch length observations during initial storage ring operation, short bunch measurements in low-alpha mode, and observations of bunch lengthening as a function of single-bunch current. For each selected bunch, a region of interest is defined on the streak image, the longitudinal projection is converted into the temporal bunch distribution, and the bunch length is obtained from the sigma of a Gaussian fit. More recently, these measurements have been extended to bunch behavior under operation with the passive SRF HC. The TPS storage ring has 864 RF buckets. For different fill patterns and SRF HC gap voltages, the results allow comparison of bunch lengthening among individual bunches and along the multi-bunch train. Under quasi-uniform filling patterns, the bunch-length variation along the train is taken here as a qualitative indication of transient beam loading. Under operation with the passive SRF HC, the bunch-lengthening factor and its bucket-dependent distribution also show how the harmonic cavity changes the longitudinal bunch distribution. A truly uniform filling pattern, with all buckets filled and equal bunch current, is expected to give a more concentrated bunch-length distribution. However, the present TPS injection condition cannot yet provide such a perfectly uniform fill, and the measured case is referred to here as a quasi-uniform fill. For a quasi-uniform fill at 500 mA,

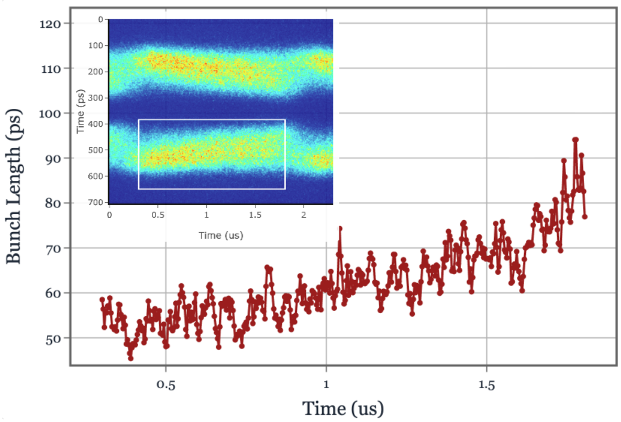

Figure 4: Measured bunch length distribution under SRF HC operation.

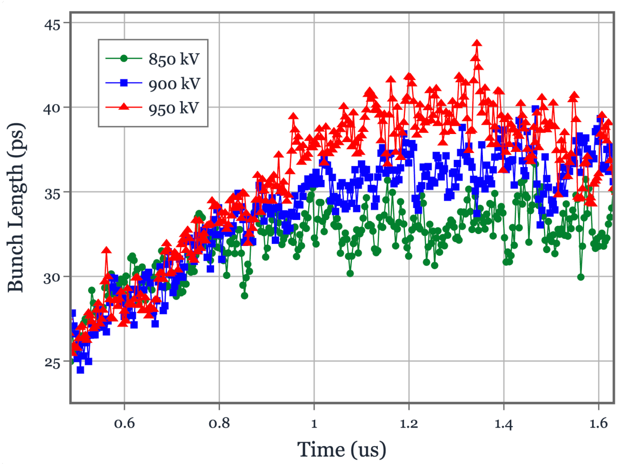

Figure 5: Bunch length variation as a function of SRF HC gap voltage.

1600 min beam lifetime, and 1000 kV SRF HC gap voltage, Fig. 4 shows bucket-dependent bunch length variation along the train from around 50 ps to 80 ps. Figure 5 compares the time evolution of bunch length measured by the streak camera at SRF HC gap voltages of 850 kV, 900 kV, and 950 kV. The raw traces show that the bunch length does not remain constant over time, but exhibits voltage-dependent trends. For a lower gap voltage of 850 kV, the bunch length decreases gradually, whereas for higher voltages of 900 kV and 950 kV, increasing or more fluctuating behavior is observed. These results indicate that the SRF HC setting influences the evolution of longitudinal bunch shape and bunch length.

Synchrotron Phase Shift Measurements on SRF HC Test

Measurements of synchronous phase shift reflect the influence of beam loading and longitudinal impedance on the bunch center position. In TPS streak camera measurements, the dual-sweep mode preserves the fast-sweep information on the y-axis and the slow-sweep information on the x-axis, so that relative phase positions of different bunches within the same fill pattern can be compared. In recent SRF HC

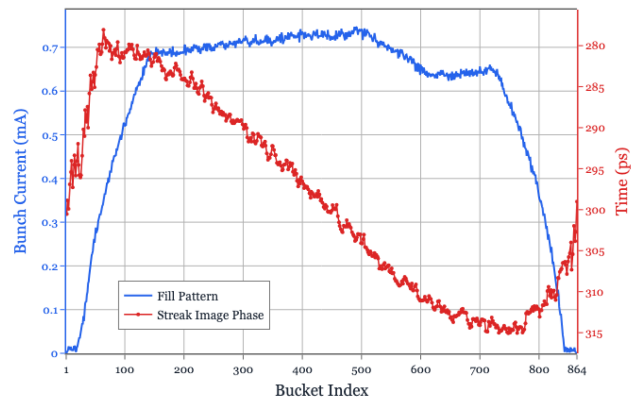

Figure 6: Dual-sweep mode streak image showing bunch-by-bunch phase distribution around the storage ring.

studies, synchronous phase shift has been one of the main observables for multi-bunch behavior. For a quasi-uniform fill pattern, transient beam loading changes the RF voltage seen by each bunch and leads to different phase-center positions along the train. In this paper, the dual-sweep streak image shows the relative phase distribution under SRF HC conditions and is compared with the bunch length results. For a quasi-uniform fill in the 864-bucket TPS storage ring at 500 mA, 650 min beam lifetime, and operation with the passive SRF HC, Fig. 6 shows a systematic phase drift along the bunch train, with a phase difference of about 35 ps between the head and tail bunches.

CONCLUSION

Streak camera measurements of a representative CU15 high-current instability case, together with bunch length and synchronous phase measurements under SRF HC operation at the TPS, have been presented in this paper. The CU15 case shows that the streak camera can record qualitative image signatures of multi-bunch longitudinal instability. Under recent SRF HC operation, the measurements were used to compare bunch behavior for different fill patterns and SRF HC settings and to follow multi-bunch variations in bunch length and synchrotron phase. These results show the present role of the TPS streak camera in longitudinal diagnostics. Future studies will compare these results with bunch-by-bunch feedback data.

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