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TIME RESOLVED DYNAMICS OF TRANSVERSE RESONANCE ISLAND BUCKETS AT SPEAR3*

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Abstract

Transverse Resonance Island Buckets have been studied at SPEAR3 as an option for timing experiment mode operation. In this mode, with proper lattice optics settings, the electron beam populates to island orbits with the excitation from a kicker. In this paper, we will report the experimental observation of beam dynamics with turn by turn beam position monitors and a fast gated camera.

INTRODUCTION

The SPEAR3 3-GeV, high-brightness third-generation storage ring, upgraded in 2004, operates at 500 mA in top-off mode, with high reliability and low emittance. Recently, there is growing interest in conducting time-resolved experiments from the user community. To enhance the timing mode experimental capability of SPEAR3 and fulfill the requirements of timing users and high-brightness users simultaneously, efforts have been devoted to develop new operation modes in SPEAR3.

Beam resonances in a storage ring are generally considered as limiting factors for the beam performance. Therefore, operational betatron tunes are chosen to avoid harmful resonance lines such as those of integer tunes and half-integer tunes. However, when a potential-well is formed around certain high-order resonances, a bunch can be trapped inside the potential-well and become stable. This so-called Transverse Resonance Island Bucket (TRIBs) mode has been studied and demonstrated at BESSY II [1] and MAX-IV [2]. Operating in this mode, it is possible to select and populate part of the bunch train on a different closed orbit from the main bunch. At the interested beamline, the unwanted X-ray from the main bunch train can be blocked to improve the signal-to-noise ratio of the timing experiment. The under-development 6 nm lattice of SPEAR3, has a designed ν_x of 15.32, which can be successfully exploited for the TRIBs studies. The TRIBs mode can be activated by either the SPEAR3 transverse multi-bunch feed back (TMFB) kicker [3] or one of the three injection kickers, K1, under slightly different lattice settings.

SPEAR3 TRIBs MODE

Tracking Simulations

Prior to our experimental studies, tracking simulations were first conducted with the 6 nm lattice to confirm the possibility for running TRIBs mode in this lattice. Using ELEGANT [4], single particles with variable initial offsets were tracked in a lattice obtained from optics fitting with LOCO [5]. The distribution of three resonance islands is visualized in the top plot of Fig. 1 as three potential wells when $\nu_x = 0.3333$. Once the electron beam is trapped in one of these islands, the new orbit (x, x'), passing through the centers of the 3 islands as shown in the bottom plot of Fig. 1, is closed every 3 turns.

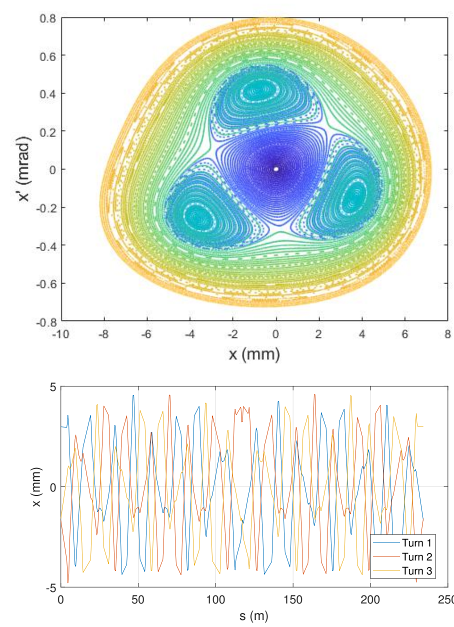

Figure 1: Closed orbit for SPEAR3 TRIBs optics.

TRIBs Excitation

The nominal chromaticity of the 6-nm lattice is +2 for both the horizontal and the vertical planes. During our TRIBs study, the horizontal chromaticity, ξ_x, was reduced to nearly 0 using a chromaticity response matrix. $\xi_x = 0$ helps to avoid tune shifts caused by momentum deviation when driving the beam horizontally. Experimentally, it was found that the TRIBs mode could be better excited when ξ_x was slightly larger than zero. We were able to drive the TRIBs mode either with the TMFB kicker or the injection kicker, K1. With the TMFB kicker, ν_x was increased to 0.3297 from the design value of 0.32 due to the relatively weak strength of the kicker. In addition, the kicker needed to be set up with a frequency sweep within a short period of time. On the other hand, the K1 kicker strength was strong enough to move the beam to the TRIBs islands with a single pulse. Because the excitation from the K1 kicker was relatively

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straightforward, it has been the main way being used for the TRIBs study at SPEAR3.

SPEAR3 has 3 injection kickers (K1, K2, K3), normally used for the closed orbit bump during off-axis injection. The K1 kicker has a calibration factor about 1.21 mrad/kV. By manipulating the kicker timing and the control software, we were able to drive the kicker in a single shot mode on demand. During the experiment, a single bunch of about 18 mA was filled initially and the K1 strength was swept in steps for TRIBs excitation, while the bunch current was decaying.

Diagnostics Tools

The TRIBs excitation in steady state can be observed by an x-ray pinhole camera or a TbT BPM. SPEAR3 is equipped with one pinhole camera and two SPARK TbT BPMs [6]. However, due to the relatively low beam current, the X-ray intensity was low and the exposure time of the pinhole camera needed to be as long as 1.5 second for good signals. The visible diagnostic beam line (Synchrotron Light Monitor, or SLM) at SPEAR3 has a fast gated, image-intensified PiMax camera. With a minimum gating time of 2 ns, the PiMax camera can image the single bunch in SPEAR3 on a single-pass basis. Along with the two TbT SPARK BPMs, they are effective tools to probe TRIBs dynamics. In Table 1, we list the twiss parameters at the injection kicker K1, the source point of the pinhole camera, the source point of SLM, and the two TbT BPMs.

Table 1: Twiss Parameters at Selected Locations

	β_x(m)	α_x	β_y(m)	α_y
K1	9.72	-0.07	4.52	-0.17
pinhole	0.55	-0.18	15.57	-0.28
SLM	1.55	1.56	14.16	-2.47
TbT1	2.79	2.38	12.30	-3.04
TbT2	8.34	-7.32	10.56	6.30

Experimental Observations

The TRIBs orbit separation was observed for a wide range of K1 settings from 0.3 kV to 0.55 kV with various bunch currents. In Fig. 2, we show an example of such observations. As mentioned earlier, the synchrotron radiation intensity was low, as a result, the exposure time of the x-ray camera was increased to 1.5 second in order to capture the beam image. Though the separation of the TRIBs orbits are larger than the field of view of the camera sensor, it was still clear that, after a single kick from K1, the beam was moved from the core, i.e. the default orbit before the kick, to three island orbits. This is also illustrated by the projection of the beam images to the horizontal axis in Fig. 2. The data from the TbT BPM1 shows three parallel lines, through which the turn-by-turn orbit cycles. The TbT BPM measures the centroid obit of the whole beam, which concurs with the TRIBs closed orbit only when all particles are in the same island. Tracking simulations results in the bottom right figure show that the island separation distance agrees well with the orbit data measured by the TbT BPM1. This implies that all particles in the bunch were kicked into one island rather than being distributed to three islands. This was further verified by the measurement with the fast gated camera as shown in Fig. 3.

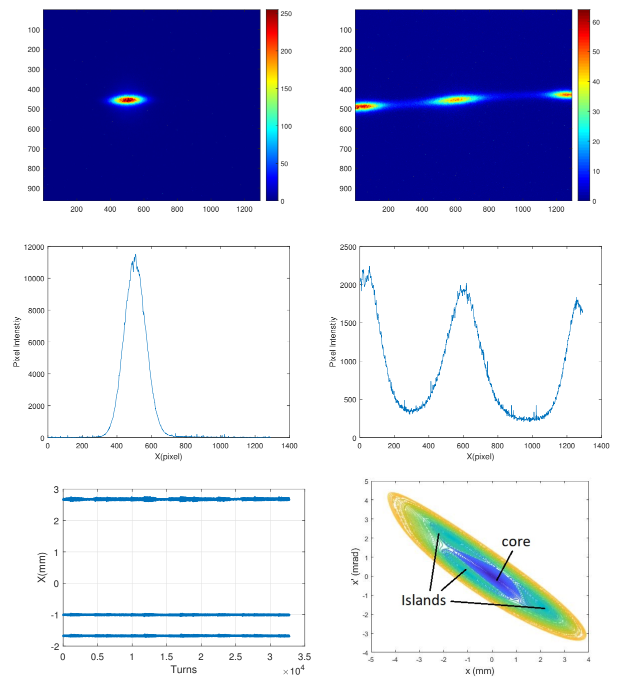

Figure 2: Experimental observations of TRIBs with a single bunch of 17 mA: x-ray pinhole images before (top left) and after (top right) the K1 kick; the projection of the pinhole images to the horizontal axis (middle); TbT BPM1 data for 32,760 turns or 25.6 ms, after the K1 kick (bottom left); island distribution at the location of TbT BPM1.

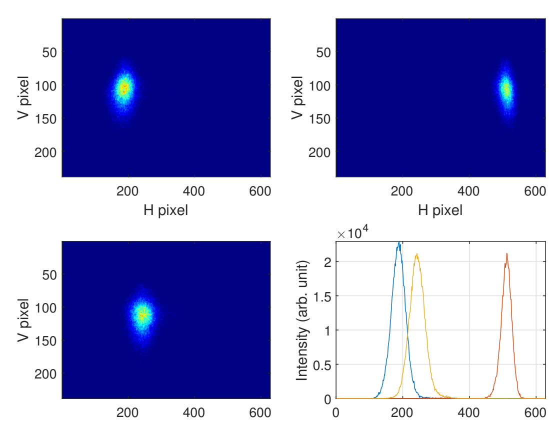

Figure 3: Single turn imaging of the TRIBs beam at 12 mA with the intesity projection to the horizontal axis.

The exposure time of the PiMax camera was set to 100 ns for single turn imaging and we took multiple images of the

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beam after the 12 mA single bunch was excited to the stable TRIBs orbit. All the images indicated that the whole bunch was moving through 3 closed orbit position as shown in Fig. 3. One should note that the visually large vertical beam size in the PiMax images was due to the diffraction-limited visible SR beam and instrumentation distortion.

It is worth noting that the beam stayed in the TRIBs orbit for as long as 20 minutes without any sign of damping down to the core orbit. In order to damp the beam back to the core, we needed to fire the K1 kicker again. This was consistent for TRIBs excitation when the single bunch current was high, e.g. larger than 6 mA. However, for lower bunch current, e.g. below 3 mA, the results were less consistent and the beam tended to damp down to the core obit within 60 seconds or less without an additional kicking.

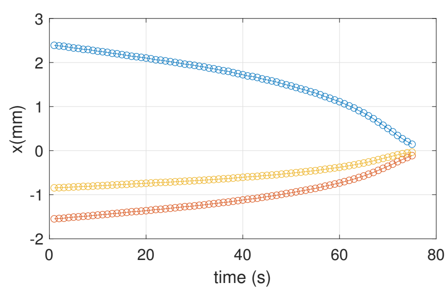

Figure 4: Orbit displacement of the single bunch 3.25 mA beam decreases over time.

In Fig. 4, we show the measured centroid orbit separation reduced over 75 seconds for a single bunch 3.25 mA beam after it was excited to the TRIBs orbit. The data were obtained from the average island orbit of the TbT BPM1 data taken at the rate of once a second. To understand the current dependent effects for the TRIBs excitation, we were motivated to measure the transient dynamics during the excitation.

TIME RESOLVED TRIBS DYNAMICS

Timing Setup

In order to better understand the beam dynamics of the TRIBs excitation, particularly the bunch current dependent effects in our study, we conducted a series of experimental measurements to probe the transient dynamics of TRIBs excitation. For these measurements, we needed the capability to capture both the transverse profiles of the beam and the beam position with turn-by-turn resolution for a single bunch in SPEAR3. This required us to synchronize the data acquisition of the fast gated PiMax camera and the TbT BPMs with the single-shot excitation from K1.

The timing set up to synchronize each different diagnostics is summarized in Fig 5. Because the trigger units for each diagnostic tool were located in different physical locations, multiple SRS Delay Generators were used for the timing setup. An SLM-DG645 was set up in the SLM with the 1.28 MHz ring revolution clock as the input trigger but decimated it to 10 Hz before sending to the B117-DG535

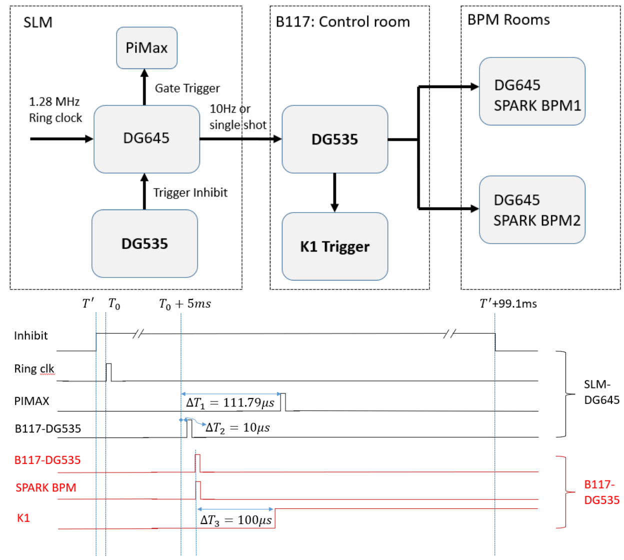

Figure 5: Timing setup and timing diagram.

in the control room as an input trigger. The reason for decimation to 10 Hz is to avoid over-driving the 10 Hz K1 kicker. The B117-DG535 produced the trigger signals for the TbT BPMs in two BPM rooms and the K1 trigger in the control room. By adjusting B117-DG535 to delay the K1 trigger by 100 s with respect to the TbT BPM triggers, we ensured the TbT BPMs capture the data when the K1 fired. The SLM-DG645 also provided the trigger signal for the PiMax camera. Therefore, by adjusting the delay of the output trigger signals to the PiMax Camera, ΔT_1, and the B117-DG535, ΔT_2, we can adjust the timing between the K1 kicker and the PiMax camera. The empirical settings were ΔT_1=111.79 µs and ΔT_2=10 µs to capture the first turn images after the kicker was fired. To capture other turns, a delay in multiples of the 781 ns revolution time can simply be added to ΔT_1. Finally, to drive the K1 kicker, TbT BPMs, and the PiMax camera with a single synchronous shot, we utilized the inhibit function of the SLM-DG645.

Time Resolved Imaging Results

For the synchronous time-resolved measurements, a 2 mA single bunch was filled in the storage ring and was driven to the TRIBs orbits by the K1 kicker with different pulse voltages: 0.4 kV, 0.45 kV, and 0.55 kV. For each case, we configured the PiMax to take 50 images with 2 second intervals starting right after the kick was fired (t=0). This provided samples of the transverse profiles of the TRIBs excitation over a 98-second period. After examining all the beam images, it was found that for all cases, the beam damped to the core orbit within 98 seconds, a similar process shown in Fig. 4. However, with different driving strengths from K1, we did find some differences in the time resolved images.

In Fig. 6, we compared the three cases by showing the images for the first 54 seconds in intervals of 6 seconds. With the 0.45 kV kick the TIRBs orbit lasted longer than the other two cases. In addition, unlike the case for the high

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current beam, there were always some particles remaining in the core orbit not being populated into the island orbits after the K1 kick.

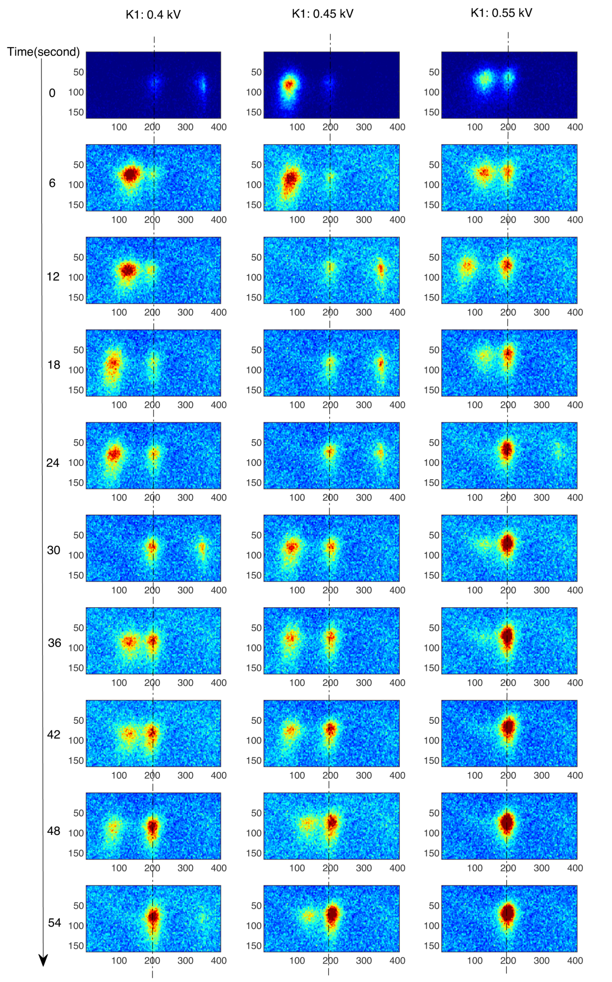

Figure 6: Time resolved TRIBs imaging for a 2 mA single bunch with K1 set to 0.4 kV, 0.45 kV, and 0.55 kV, respectively. The dash-dot lines indicate the location of the core orbit.

TbT BPM Data

The synchronized TbT BPM1 data is shown in Fig. 7 for both high and low current beam with different K1 kick amplitude. At a lower K1 voltage of 0.32 kV for a 14 mA bunch, the orbits of the high current beam slowly converged to the TRIBs orbits. The process was longer than 26 ms, but once the beam settled in the island orbits, it would stay for an extended period of time. This process was shorter when the K1 votage was increased to 0.58 kV, for which it took about 26 ms for the beam to settle in the island orbit. On the other hand, at K1 voltage of 0.35 kV for the 2 mA beam, the charge centroid orbit separation as measured from the TbT BPM never reached the full TRIBs orbit, because, as we learned from the PiMax data shown in Fig. 6, part of the beam was still in the core orbit. In the 2 mA case, without an external driving source to the TRIBs orbits, the particles would damp down to the core on the order of tens of seconds. It appears that, at 0.45 kV, the 2 mA beam was placed right to the TRIBs potential well. This is consist with the results at t=0 second in Fig. 6, which shows most of particles are on the TRIBs orbit.

In Fig. 8, the centroids of the TRIBs orbits for the 2 mA single bunch are plotted for various K1 voltages. The maximum separation of the TRIBs orbit occurs at 0.45 kV and drops significantly for 0.55 kV and 0.35 kV. This suggests that for low current bunch, the range of K1 voltage to populate all beam to the TRIBs islands is small. In Contrast, the K1 voltage requirement for the high current bunch to be driven to the TRIBs is more relaxed as shown in the data presented earlier.

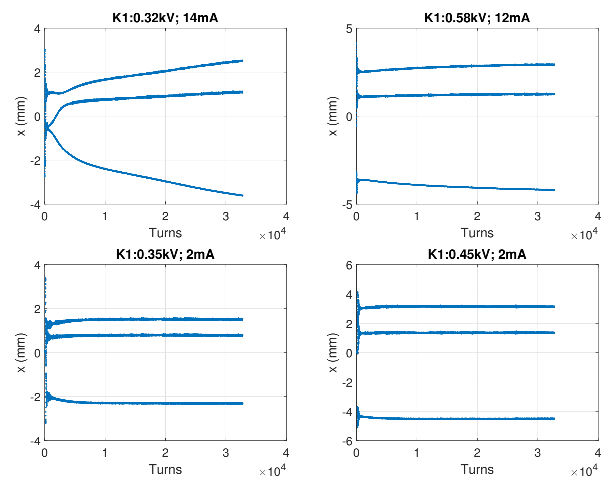

Figure 7: TbT BPM data for TRIBs excitation with different beam currents and K1 votage.

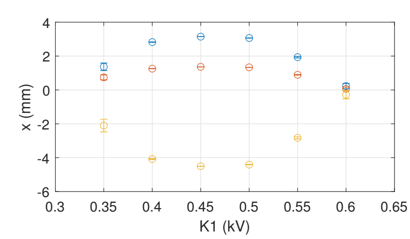

Figure 8: Measured charge centroid separation of the 2 mA single bunch changes with K1 voltage.

SUMMARY

Synchronous experimental studies on the TRIBs dynamics have been carried out in SPEAR3. We observed the current dependent effect in driving a single bunch to TRIBs using one of the injection kickers. The underlying physics is still unknown, but further studies, both experimental and theoretical, are under the way.

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