ANALYSIS OF BEAM ABORTS AT SuperKEKB WITH THE BUNCH CURRENT AND OSCILLATION RECORDER

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Abstract

In SuperKEKB, the bunch current monitor (BCM) and the bunch oscillation recorder (BOR) have been developed for the bunch-by-bunch feedback system and are also used to record the turn-by-turn (TbT) data in bunch-by-bunch (BxB) mode prior to each beam abort. The causes of the beam aborts can be diagnosed using the dedicated beam abort monitor system. Meanwhile, the BCM/BOR data can provide additional information concerning beam instabilities. For example, the TbT patterns of the BOR data can show a clear correlation with hardware malfunctions. The BxB tunes can be extracted from spectrum analysis of the TbT data, showing certain modes of beam motions. This work reports the preliminary analyses of BCM/BOR data from various beam aborts at SuperKEKB. It represents an effort of correlating the beam aborts with possible hardware malfunctions or beam instabilities.

INTRODUCTION

The SuperKEKB project has two storage rings to store high-intensity beams of electron and positron for collision. In each ring, an abort system [1] is designed to kick the stored beam out to a dump to protect the Belle2 detector and other accelerator components from damage. The abort trigger system works to collect requests from various interlocked subsystems, and the abort monitor system works to collect data of abort events for later analysis [2]. The post-analysis based on the beam abort monitor system has been successful in identifying the causes of aborts [2].

In addition to the beam abort monitor system, the bunch-by bunch (BxB) current monitors (BCMs) and oscillation monitors (BORs) are also very useful for the analysis of beam aborts. The BCMs and BORs have been routinely used as beam instrumentation for the BxB feedback system of KEKB [3] and SuperKEKB [4]. From the analysis of BOR data, the electron-cloud instability was identified in KEKB LER [5, 6]. When beam aborts happen, the rapid change of beam currents in the rings triggers the BCMs and BORs to record 4096 turns of data for all 5120 RF buckets. The data are then transferred to a remote hard disk for post-analysis. Since the BCM and BOR data are linearly proportional to the bunch charge and the amplitude of beam motions respectively, they can be used to analyse the beam aborts with focus on beam dynamics. The preliminary results are presented in this paper.

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DATA ANALYSIS

The raw data saved by BCMs and BORs in ADC format are translated to text format. A dedicated Octave [7] code was developed to read the text files and then plot the data and perform Fourier analyses. The BCM data contain information of bunch currents with the filling pattern defined by the bucket selection system. The arbitrary position of 0th bucket for the BCM/BOR data is unknown. For each abort, the BOR data contain three files corresponding horizontal, vertical and longitudinal motions respectively. We use the BCM data as a reference and circularly shift the BOR data in each direction to find a best match. This matching process is done automatically and double checked visually. The amount of bucket shifts in each direction of motion is a constant and can be used in the analyses of all aborts unless the hardwares of BCM/BOR system are changed. Figure 1 shows an example of BOR data synchronized to BCM data in HER.

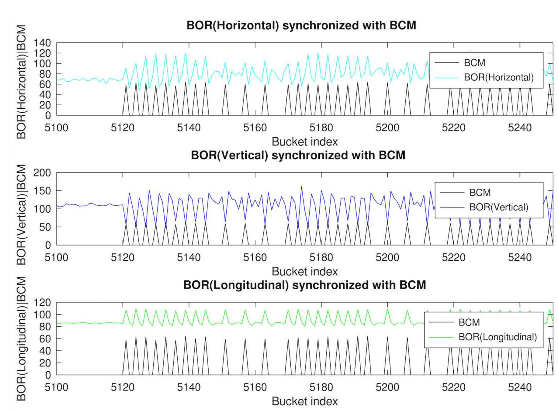

Figure 1: Example of sychronization of BOR data to BCM data for HER.

Manual abort

During the beam commissioning, sometimes the beams need to be dumped on purpose and the operators use a switch to trigger the beam abort manually. Figure 2 shows 8 turns of BCM/BOR data for a manual abort during the physics run of SuperKEKB. The data were recorded at 08:04 AM, May 26, 2021 with currents of 680 and 840 mA for HER and LER respectively, and the total number of bunches was 1174 for each ring. Before the beam abort, the beams were stable with every hardware subsystem working well. The BxB data of the filled buckets for about 4080 turns before the abort are plotted in Fig. 3. The variation of color in bucket index is attributed to the fluctuation of bunch currents. There is no evident variation of color in turn, indicating the beams are stable before the abort was triggered.

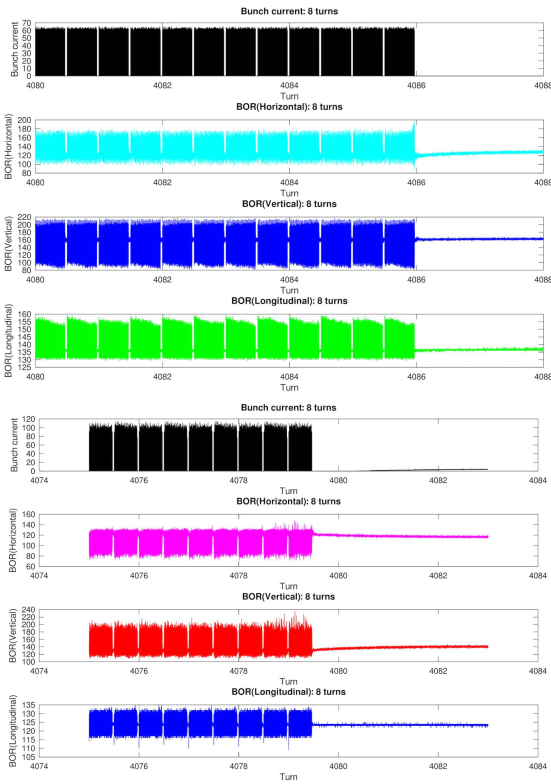

Figure 2: BxB BCM/BOR data of 8 turns around beam abort of HER (upper) and LER (lower) for a manual abort.

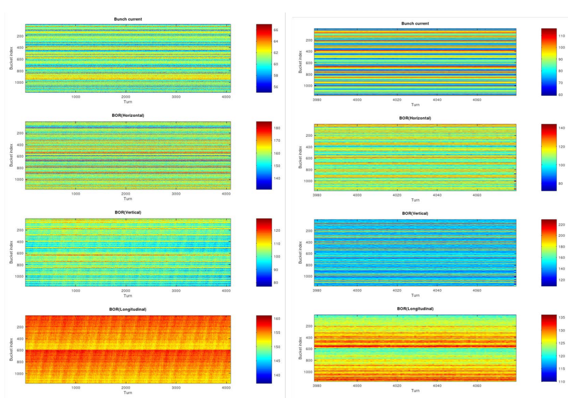

Figure 3: BxB BCM/BOR data of about 4080 turns for the filled buckets of HER (left) and LER (right) for a manual abort.

The Fourier power spectrum of each bucket is calculated using 4096 turns of data separately, and then the power spectra of all filled and empty buckets are averaged respectively. The results are shown in Fig. 4 with the horizontal scale in units of fractional tune. The power spectra of empty buckets are plotted in black lines indicating pedestals of noise. The vertical betatron peak is visible around 0.585 in HER, and the longitudinal synchrotron peak is visible around 1-ν_s with ν_s=0.0235 in LER. The other peaks in the spectra of betatron and synchrotron motions are believed to be noises introduced to the FB system from environment. Especially, the noises in FB system of HER were identified and removed successfully since Jun. 29, 2021.

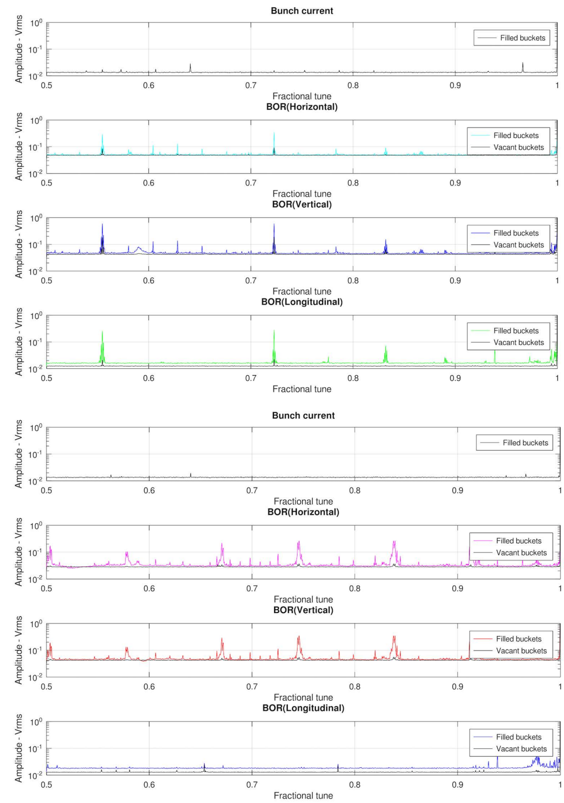

Figure 4: Average spectra of filled buckets compared to that of empty buckets of HER (upper) and LER (lower) for a manual abort.

The coupled-bunch modes are also calculated by following the method in Sec. III of Ref. [6]. The results are shown in Fig. 5. The beam spectra are plotted on the top of each sub-figure with their pattern determined by the filling pattern. For this case, the bunch spacing is a mixing of by 3 and by 6 RF buckets with two ion clearing gaps. The indices of the strongest 3 beam modes are identified as 0, 1672, and 3448, corresponding to bunch spacing of 3.06 buckets calculated directly from the filling pattern.

The results of data analysis for manual abort serve references to identifying causes of various abnormal aborts as will be discussed in the following subsections.

Identified aborts

In SuperKEKB, some types of beam aborts can be well understood through the recorded data of the dedicated beam abort monitor system and also the logged data of hardware subsystems [2]. Meanwhile, the BCMs and BORs provide consistent information for these aborts. Here we present examples of BCM/BOR data analysis for: 1) aborts correlated to LER injection kicker mismatch; 2) aborts correlated to

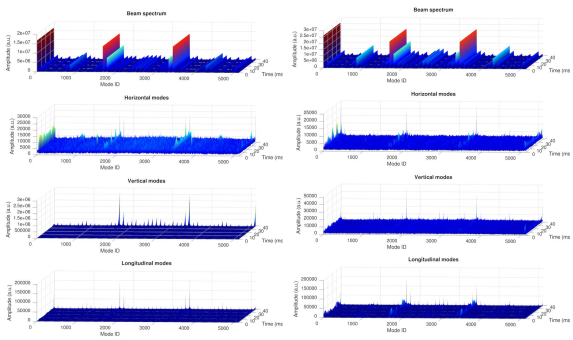

Figure 5: Time evolution of coupled-bunch modes of HER (left) and LER (right) for a manual abort.

earthquake; 3) aborts correlated to beam phase drift because of RF down.

Injection kicker mismatch in LER During the beam commissioning of SuperKEKB, sometimes the horizontal motion of LER beam was excited, resulting in extra beam losses that were detected by Belle2 or by loss monitors. From BOR data, it can be clearly seen that part of the bunch train had large oscillation in the horizontal plane before abort (see Fig. 6 as an example recorded at 18:39 PM, Jun. 24, 2021). The range of the excited bunches along the train is comparable to the duration of the injection-kicker waveform. More careful analysis of the injection system showed a mismatch of the injection kickers was the source of such beam aborts.

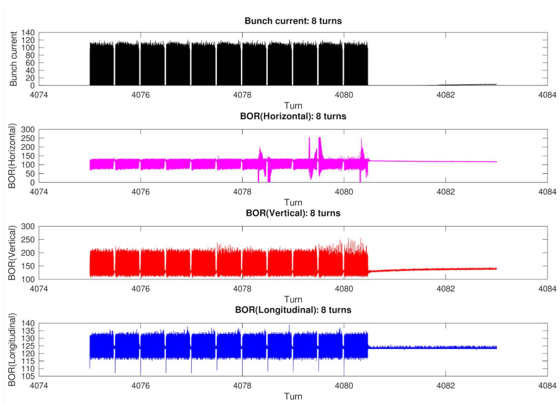

Figure 6: BxB BCM/BOR data of 8 turns around beam abort of LER for an abort correlated with mismatch of injection kickers.

Earthquake Earthquake frequently causes beam aborts at SuperKEKB. When an earthquake occurs, the hardware components in the rings vibrate together with the ground motion. This leads to the drift of beam orbit. A typical example recorded at 23:40 PM, May 30, 2021 is shown in Figs. 7 and 8 for HER. The transverse motion is modulated in the frequency of around 1 Hz. The modulation in horizontal motion is visible but less profound than in the vertical direction. The BCM/BOR data of LER have similar patterns.

The Belle2 detectors detected abnormal beam losses and triggered the abort.

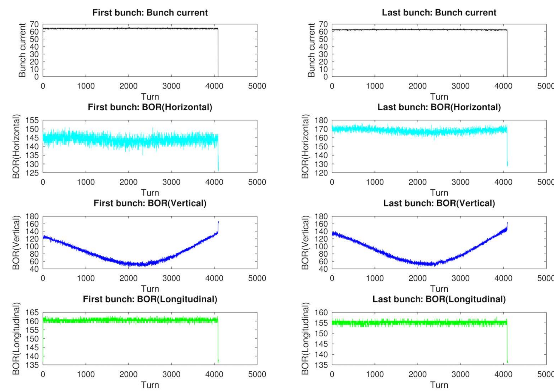

Figure 7: TbT BCM/BOR data of the first (left) and last (right) bunches of HER with the abort correlated to an earthquake.

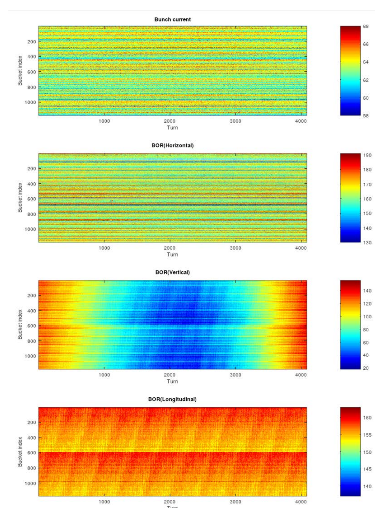

Figure 8: BxB BCM/BOR data of about 4080 turns for the filled buckets of HER with the abort correlated to an earthquake.

Beam phase Figures 9 and 10 (data recorded at 23:18 PM, Jun. 15, 2021) show an example of aborts correlated to beam phase drift. In this abort, one RF cavity was down, causing significant shift in beam phase in the time scale of 10 turns. The RF system detected the abnormal beam phase and triggered the abort. One can see that the beam phase shift causes modulations in all BCM/BOR data, indicating excitation of betatron and synchrotron motions.

Unidentified aborts

In contrary to the well-understood beam aborts, some aborts still remain to be understood. From BOR/BCM data, these unidentified aborts had features of: 1) Sudden beam loss happened in a few turns; 2) The beam loss rate varied time by time; 3) The large beam losses to IR region

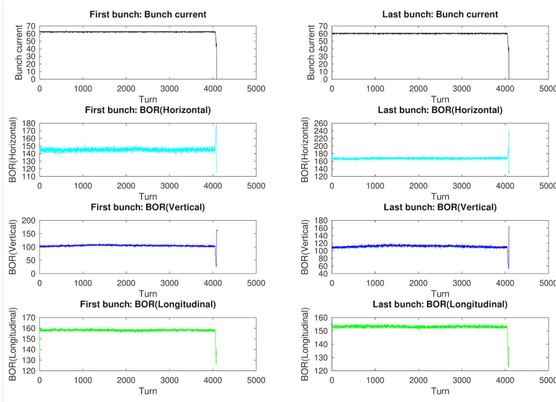

Figure 9: TbT BCM/BOR data of the first and last bunches of HER with the abort correlated to beam phase drift.

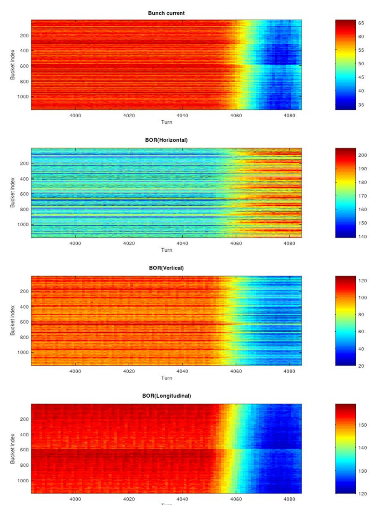

Figure 10: BxB BCM/BOR data of about 4080 turns for the filled buckets of HER with the abort correlated to beam phase drift.

even caused quenches of superconducting QCS magnets; 4) Before the sudden beam loss, no clear signs of single- or coupled-bunch instabilities were detected. We show some examples of such unidentified aborts.

Sudden beam loss in HER Figure 11 shows an abort triggered by Belle2 CLAWS detector around 04:29 AM, Jun. 21, 2021. It was related to sudden huge beam loss in one turn in HER. From the BCM data, the TbT beam losses are calculated for each filled bucket. The TbT beam spectra and coupled-bunch modes (not shown in this paper) are very similar to those of manual aborts if the last few turns before abort were excluded. There was no clear evidence of large orbit oscillation before the beam loss started.

Figure 12 shows another abort triggered by Belle2 CLAWS detector around 01:22 AM, Jun. 22, 2021. It was related to sudden small beam loss in HER. Except the beam loss rate, the beam phenomena observed via BCM/BOR are very similar to the previous case. It seems that such aborts

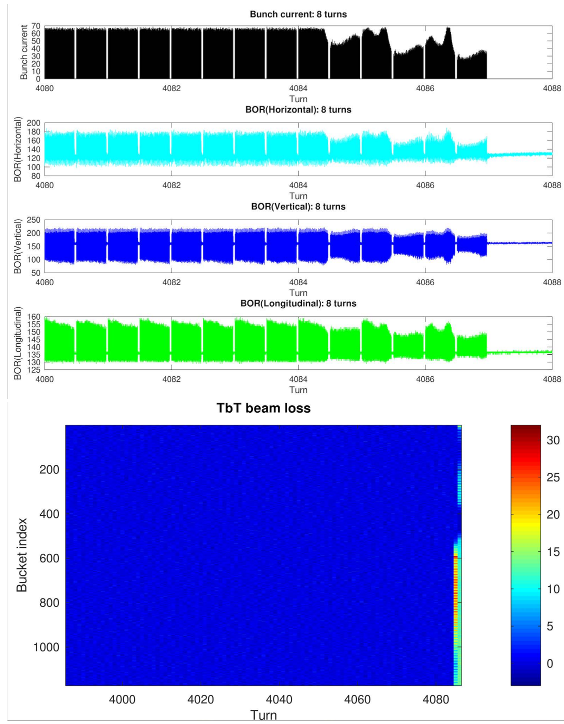

Figure 11: BxB BCM/BOR data of HER with sudden huge beam loss (Upper: BCM/BOR data in 8 turns; Lower: TbT beam loss in 100 turns for filled buckets).

due to sudden beam losses can be classified into the same type.

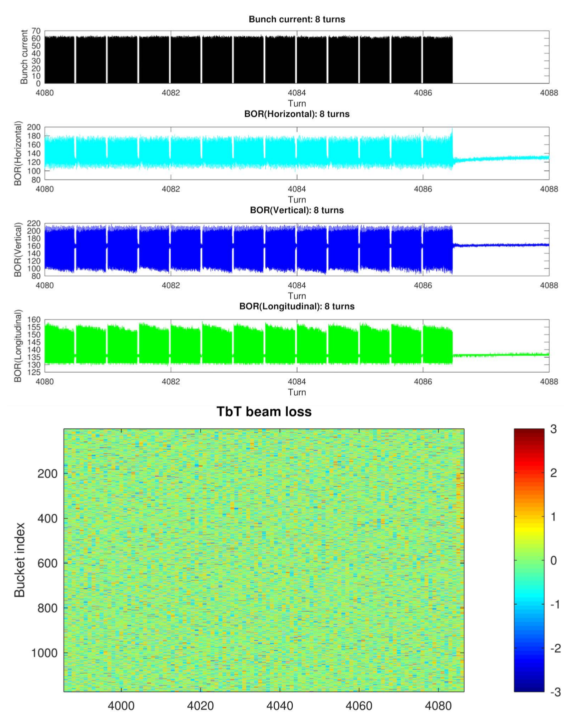

Figure 12: BxB BCM/BOR data of HER with sudden small beam loss (Upper: BCM/BOR data in 8 turns; Lower: TbT beam loss in 100 turns for filled buckets).

Sudden beam loss in LER Similar to HER, sometimes sudden beam losses occured in LER. Figures 13 (recorded at 20:13 PM, Jun. 2, 2021 with QCS quench) and 14 (recorded at 13:41 PM, Jul. 2, 2021) show the cases of huge and small beam losses respectively.

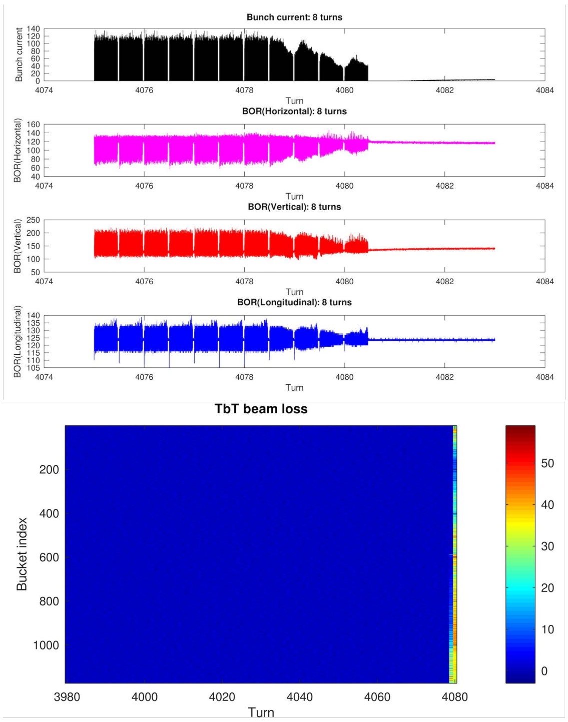

Figure 13: BxB BCM/BOR data of LER with sudden huge beam loss (Upper: BCM/BOR data in 8 turns; Lower: TbT beam loss in 100 turns for filled buckets).

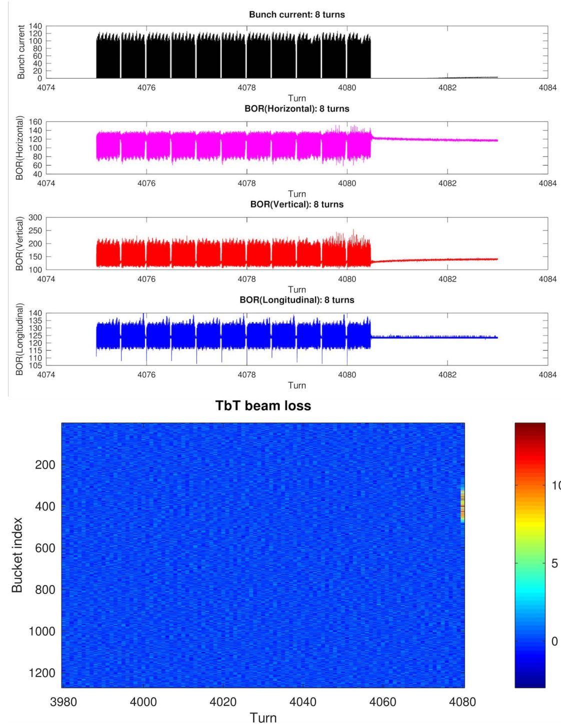

Figure 14: BxB BCM/BOR data of LER with sudden small beam loss (Upper: BCM/BOR data in 8 turns; Lower: TbT beam loss in 100 turns for filled buckets).

SUMMARY AND DISCUSSION

Various types of aborts are examined through the data recorded by the BCM/BOR system of SuperKEKB. The BCM/BOR data show beam dynamics for the beam aborts that have been already identified by the beam abort monitor system. But some aborts related to sudden beam losses still remain to be understood. For those aborts, both the beam abort monitor system and the BCM/BOR system provide limited information about the beam dynamics.

The BCM/BOR system is sensitive to dipole motions of the stored beam. One hypothesis is that the beam aborts caused by sudden beam losses resulted from fast growth of beam emittances, on which the BCM/BOR system would be insensitive. If this is true, TbT or even BxB beam instrumentation based on synchrotron lights instead of BPMs would be very useful. And the sources of emittance growth are also to be investigated.

Currently, simple Fourier analysis was applied to calculate the beam spectra. More advance analysis such as SVD will be tried to reduce the numerical noise in BCM/BOR data.

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