5th International Particle Accelerator Conference IPAC2014, Dresden, Germany JACoW Publishing
ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-THPRO082

OBSERVATION OF COHERENT INSTABILITY IN THE CERN PS BOOSTER*

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Abstract

At high intensities and at certain working points, an instability develops in the CERN PS Booster and large coherent transverse oscillations and beam loss occur [1]. The coherent oscillations and beam loss can be effectively controlled with the transverse damper system, but the origin of the instability is not well understood. In preparation for nonlinear optics measurements in the PS Booster that will take place after CERN's first Long Shutdown, trial measurements were made with the PSB's new trajectory measurement system. The measurements gave some new insight into the nature of this transverse instability, and these observations are presented here.

INSTABILITY AND BEAM LOSS WITHOUT TRANSVERSE DAMPER

At typical operational working points, the transverse damper effectively suppresses transverse instabilities and prevents beam loss. But when the transverse damper is inactive, the instability that occurs near 390 ms in the acceleration cycle causes about two thirds of the beam to be lost. Figure 1 shows the horizontal beam position during this instability, with both a linear and a log scale. The beam envelope growth is exponential, with a time constant of approximately $\tau = 0.45$ ms.

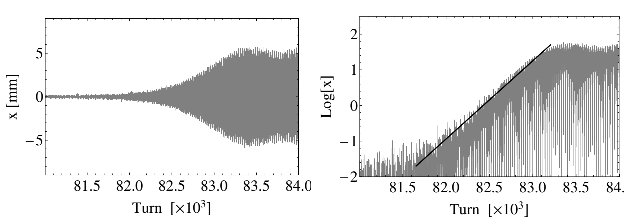

Figure 1: Horizontal beam position, shown with linear (left) and logarithmic (right) scale, during transverse instability with transverse damper deactivated.

The horizontal and vertical frequency spectra of the first 2000 turns of this instability are shown in Fig. 2. Two lines are prominently visible in the spectra of both planes, at frequencies that do not correspond to any combination of the betatron or synchrotron tunes ($Q_s \approx 0.0017$). These peaks are always visible in the spectrum, whether or not the transverse damper is active and independent of working point or beam energy. The absolute frequencies of these peaks are constant throughout the acceleration cycle, at 263.5 kHz and 296 kHz, even while the revolution frequency (and therefore the tune of these perturbing frequencies) changes.

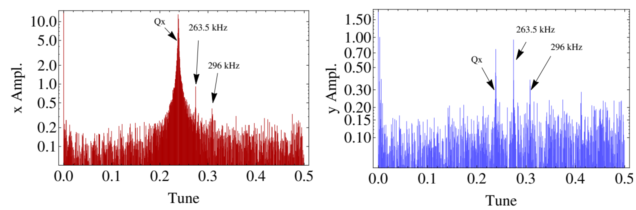

Figure 2: Trajectory spectrum during instability, with transverse damper inactive. In addition to the betatron tunes, lines at 263.5 kHz and at 296 kHz are always visible in the spectra.

A close examination of the frequencies of these peaks relative to the horizontal tune shows that there is a very specific condition under which this instability occurs. Figure 3a shows the beam intensity during 10000 turns surrounding the occurrence of the instability, with losses beginning around turn number 83500. Figure 3b shows the evolution of the horizontal tune and of the 263.5 kHz and the 296 kHz spectral lines during the same 10000 turns. The revolution frequency is increasing at this point in the acceleration cycle, so the tunes of the 263.5 kHz and 296 kHz lines are decreasing slightly from turn to turn, getting closer to the horizontal tune. No external excitation is applied to the beam, so for the first few thousand turns the horizontal tune is not clearly readable. The tune becomes clear as the horizontal instability develops, but still a few thousand turns before beam loss occurs. Figure 3c shows the frequency difference between the 263.5 kHz and the 296 kHz spectral lines, and the frequency difference between the 263.5 kHz line and the horizontal tune. The beam loss occurs precisely when the separation between all three spectral lines is equal.

This relationship between the frequencies suggests that the 296 kHz peak may be a side band of the 263.5 kHz peak, and the instability occurs when the tune falls on another, smaller sideband which may not be visible above the noise floor in the spectrum. Under certain conditions a peak is visible at around 32.5 kHz (see Fig. 4), which supports this idea, but these observations need further study in order to be fully understood.

INSTABILITY WITH TRANSVERSE DAMPER

In certain circumstances, this instability is strong enough to result in beam loss even when the transverse damper is active. This was only observed to happen at atypical working points, such as during chromaticity measurement scans. In one such case, the instability occurs at approximately

* This research project supported by a Marie Curie Early Initial Training Network Fellowship of the European Community's Seventh Framework Programme under contract number (PITN-GA-2011-289485-OPAC)

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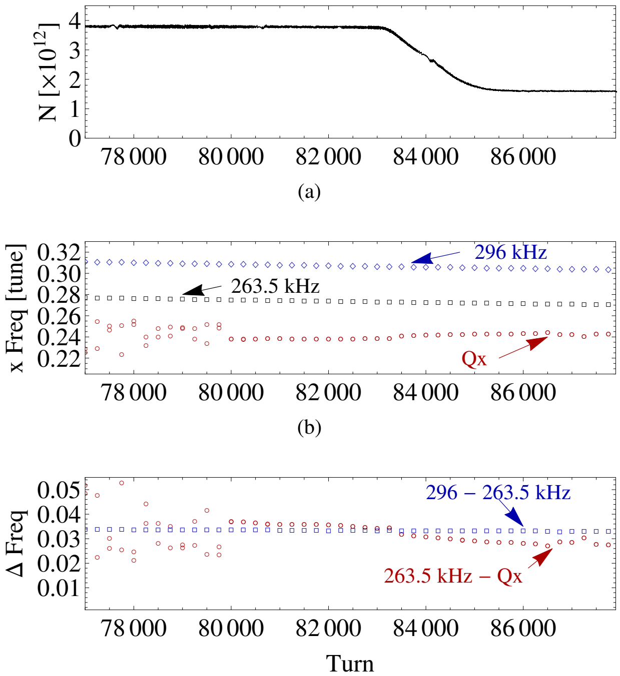

Figure 3: (a) Beam intensity, (b) horizontal tune, and 263.5 kHz and 296 kHz lines (in tune units), and (c) difference between tunes of 263.5 kHz and 296 kHz lines, and between 263.5 kHz line and horizontal tune. Beam loss occurs precisely when the separation between the three spectral lines is equal.

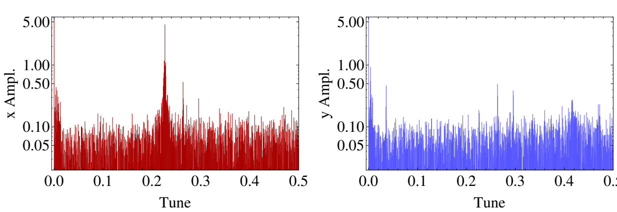

Figure 4: Beam spectra with $\xi_x = 0$ and small transverse oscillation from tune kicker. Revolution frequency is 1 MHz. A pair of low-frequency spectral lines separated by 32.5 kHz (at 0.004 and 0.0365) is visible in the vertical plane.

103,000 turns, or 415 ms, into the acceleration cycle. The chromaticity was corrected in the vertical plane, the vertical tune was $Q_y = 4.338$, and the horizontal tune was varied in steps between about $Q_x = 4.18$ and $Q_x = 4.36$ by adjusting the momentum offset.

Figure 5 shows the beam trajectory in both a linear and logarithmic scale when this instability occurs. Again the growth is exponential, but with a time constant of about $\tau = 0.85$ ms (compared to $\tau = 0.45$ ms for the case shown in Fig. 1). This slower growth is likely due to the fact that the damper is working to suppress the instability but is not strong enough to fully suppress it. Figure 6 shows the horizontal and vertical spectra of the first 2000 turns of the instability. Instability only occurred when the horizontal tune fell between the 263.5 kHz and 296 kHz spectral peaks, and only developed after the beam was perturbed by the tune pinger. At other working points encountered during the chromaticity scan, the damper was strong enough to prevent the growth of coherent oscillations.

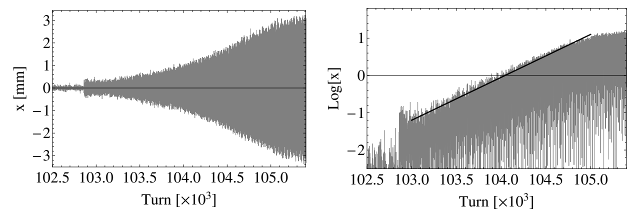

Figure 5: Horizontal beam position, shown with linear (left) and logarithmic (right) scale, during transverse instability with transverse damper active, $Q_x = 4.29$, $Q_y = 4.34$, $\xi_y \approx 0$. Instability occurs only after perturbation with the tune pinger, and grows slowly because it is partly suppressed by the damper.

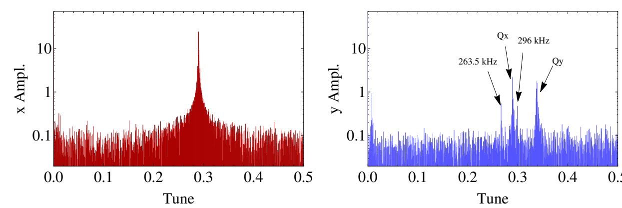

Figure 6: Beam spectra during instability while transverse damper active. In similar measurements Q_x was changed by altering the momentum offset, and instability only occurred when Q_x fell between the 263.5 kHz and the 296 kHz peaks.

TUNE SCANS

The instability related to a horizontal tune of ≈ 4.29 was also observed in tune scans that were performed for resonance mapping. Figure 7 shows the results of tune scans in which the horizontal tune is held fixed, and the vertical tune is scanned from 4.4 to 4.1 during the 160 MeV energy plateau of the acceleration cycle. The horizontal tune is stepped in increments of 0.01 on different pulses. The color corresponds to the slope of the beam intensity when scanning through a given working point.

A distinct region of high losses is seen when $Q_x = 4.29$ – 4.30 and $Q_y < 4.24$, which does not lie on any of the primary resonance lines. The beam loss is very sudden, with large losses occurring in a matter of a few milliseconds, which is a characteristic typical of losses due to instabilities rather than resonances. In similar tune scans where the vertical tune was held constant and the horizontal tune was swept from 4.10 to 4.40, no losses were observed in this region. The transverse damper was active during these measurements, but it apparently was not strong enough to keep the instability suppressed in the case when the horizontal tune was held fixed at this dangerous working point.

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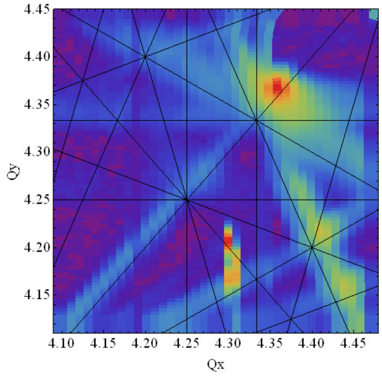

Figure 7: Tune scan performed without correction of closed orbit distortion. Color corresponds to change in beam intensity while Q_y is varied and Q_x is held fixed. Losses are observed when $Q_x \approx 4.30$.

The tune scan shown in Fig. 7 was done with no closed orbit correction. This measurement was later repeated with the PSB's new closed orbit correction system in use, and the loss pattern at $Q_x \approx 4.30$ disappeared (see Fig. 8). This suggests that the perturbation might be associated with a quadrupole field, and so acts on the beam more strongly when the beam passes far from the center of the beam pipe.

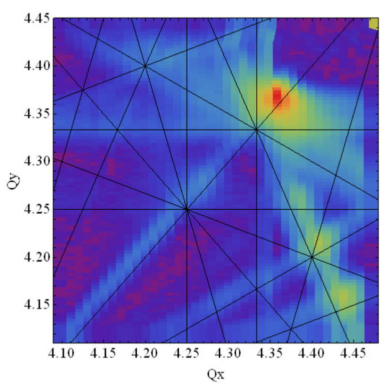

Figure 8: Tune scan performed with closed orbit distortion corrected. Beam loss pattern near $Q_x \approx 4.30$ (see Fig. 7) is no longer observed.

SIMULATIONS WITH QUADRUPOLE NOISE

A few characteristics of the observed instability suggest that it may be related to a quadrupole perturbation, such as the fact that the effect of the instability is greater when the closed orbit distortion is large and vanishes when the closed orbit is corrected (see Figs. 7,8). The 32 quadrupoles in the ring are all powered on the same circuit, and each of the 16 periods is separated by ≈ 90 degrees in betatron phase advance. It is possible that a perturbation in the quadrupole power supply, modulated by the frequency with which the circulating beam encounters each quadrupole, could produce a combination of frequencies that could drive an instability.

To explore this possibility, a simple simulation was made with jitter added to the triplet quads in the machine lattice. The focusing quads were known to have had sizable current jitter at 1200 Hz before LS1, so perturbations at 1200 Hz, plus the 32 kHz frequency suggested by measured spectra, were added to the model quadrupoles. The amplitude was larger than would be realistic, but the addition of this large quadrupole jitter does produce several new peaks at frequencies similar to those observed from measured trajectories.

For comparison, the spectrum from this simulation is shown along with the measured spectrum from the Q meter, recorded during studies of this instability in January 2013 (see Fig. 9). The signal from the Q meter pickup is processed to make it sensitive to small oscillations, so it has better resolution than the spectra from the BPMs [3]. Though the working point is not the same for both of these cases, and it is possible that the structure seen in the Qmeter spectrum is due to some nonphysical cause such as amplifier saturation, it is still interesting to note that there are similarities to the structure in each case, such as the peak near 32.5 kHz.

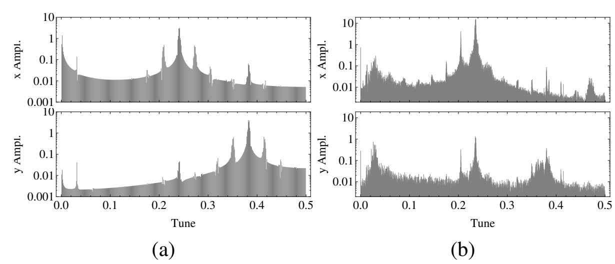

Figure 9: (a) A simple model showing beam trajectory with a large quadrupole perturbation at 1200 Hz and 32.5 kHz; (b) trajectory from the PSB tune meter during instability.

CONCLUSIONS

Measurements made with a prototype trajectory measurement system have provided some interesting new clues about a transverse instability that has long been observed in the PSB, but as yet we do not have enough information to draw solid conclusions. The behavior of the instability seems consistent with a quadrupolar perturbation, so it may possibly be related to a large ripple in the focusing quadrupole magnets' power supply which was observed before LS1. After LS1, we will attempt to determine the physical location of the perturbation by measuring the trajectory with BPMs all around the ring, and then identifying any unexpected phase jump between adjacent periods.

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