SPECTRAL ANALYSIS OF COUPLED-BUNCH INSTABILITIES IN THE BESSY-II STORAGE RING*

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Abstract

In order to characterize longitudinal and transverse coupled-bunch oscillations in the BESSY-II storage ring, beam spectra were recorded under different beam conditions. The information on longitudinal instabilities was complemented by time-domain data from the digital longitudinal feedback system.

1 INTRODUCTION

BESSY-II is a high-brilliance synchrotron radiation source in Berlin-Adlershof. The storage ring was commissioned in 1998, regular user operation started in 1999 [1]. Transverse coupled-bunch instabilites, already showing up at low beam current, could be cured by increasing the horizontal and vertical chromaticities $\xi_{x,y} = \Delta Q_{x,y}/(\Delta p/p)$ to values of ∼5 at the cost of beam lifetime. Longitudinal coupled-bunch oscillations initially started around 40 mA. Installing damping antennas in the four DORIS-type 500 MHz cavities [2] raised the theshold significantly. In fall 1999, longitudinal and transverse bunch-by-bunch feedback systems [3] [4] were commissioned that controlled all instabilities up to the largest achieved beam current of 400 mA.

Since then, the impedance budget of the storage ring was increased considerably:

- Four passive 3rd-harmonic cavities, installed in November 1999 to improve the Touschek lifetime by bunch lenghtening, introduced new longitudinal instabilities driven by their higher-order modes (HOMs).
- Insertion device chambers with small vertical apertures (± 5.5 mm) increased the resistive-wall impedance.

Futhermore, passive harmonic cavities cause large synchronous phase transients in non-even fill patterns. In order to meet these new challenges for the feedback systems, a closer look was taken at the coupled-bunch oscillations encountered so far.

2 METHODS

The most obvious tool to study coupled-bunch instabilities is a spectrum analyzer connected to a pickup electrode. However, the full content of a beam spectrum is not always easy to visualize. At the full span of 250 MHz (in which all multibunch modes can be found), revolution harmonics cannot be distinguished from lower or upper synchrotron sidebands or from betatron lines. It is therefore neccessary to look at the vicinity of each revolution harmonic individually with high resolution, and to present the data in a comprehensible way. For this purpose, a spectrum analyzer (HP-8596E) was controlled by and the data transferred to a computer using LabVIEW [5]. With $h = 400$ revolution harmonics and ~ 1 s per sweep, a typical data set was obtained within 7-8 minutes while the beam current decayed by a few percent.

For longitudinal instabilities, the data recording capability of the longitudinal feedback system (LFB) was employed. The data buffer can store oscillation amplitudes of all bunches sampled over 30-50 ms, depending on the sampling rate. Most of the offline analysis of LFB data is done using MATLAB routines [6]. Fourier transform of bunch amplitudes yields a pseudo-spectrum of longitudinal multibunch modes, and - in contrast to spectrum analyzer measurements - this time-domain approach allows to study the time evolution of oscillations such as growth, damping, sawtooth behavior, or beating between modes.

Other time-domain techniques, also applied at BESSY-II to observe multibunch oscillations, are streak camera imaging [2] and recording pickup signals with a digital oscilloscope triggered at the nominal bunch passage [7].

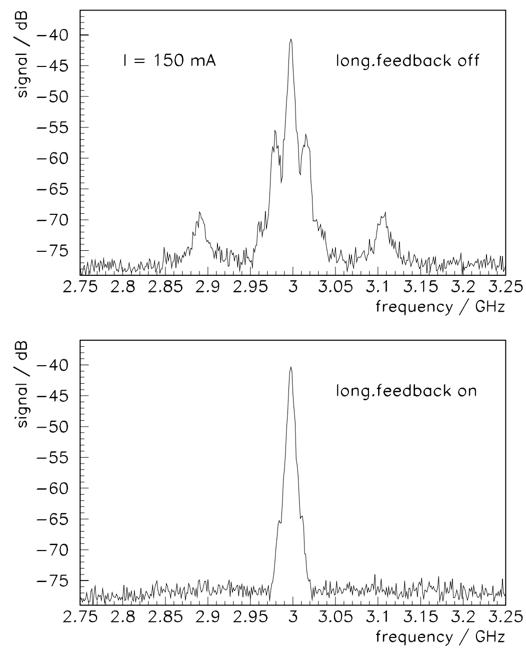

Figure 1: Beam spectrum with LFB swithed off (top) and on (bottom), prior to the installation of harmonic cavities.

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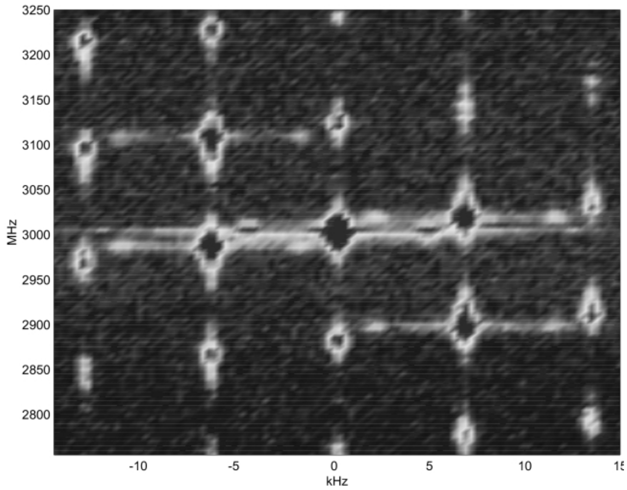

Figure 2: Sequence of spectrum analyzer sweeps of 30 kHz span (horizontal axis) centered at revolution harmonics from 2.75 GHz to 3.25 GHz (vertical axis) prior to the installation of harmonic cavities.

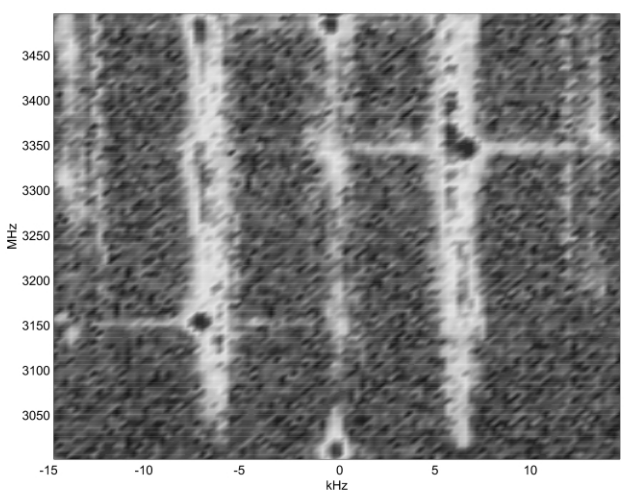

Figure 3: Sequence of spectrum analyzer sweeps of 30 kHz span (horizontal axis) centered at revolution harmonics from 3.00 GHz to 3.50 GHz (vertical axis) after the installation of harmonic cavities.

3 LONGITUDINAL INSTABILITIES

Prior to the installation of harmonic cavities, the beam spectrum above 100 mA looked typically like shown in figure 1 over a span of 500 MHz. With the LFB on, the spectrum was flat apart from the rf harmonics broadened by the uneven fill pattern (two bunch trains of 120 bunches each). With the LFB off, peaks ~110 MHz away from multiples of the rf frequency emerged, accompanied by further broadening of the the rf harmonics.

More of this structure is revealed when stepping through the revolution harmonics with a 30 kHz span as shown in figure 2. Each spectrum analyzer sweep creates a horizontal line of the figure. The vertical axis from 2.75 GHz to 3.25 GHz labels different revolution harmonics and hence different multibunch modes. The figure shows first and second synchrotron sidebands at ± 7 kHz and ± 14 kHz, respectively, as well as sidebands of the rf harmonics (here at 3 GHz) which are reduced to ± 5 kHz by Robinson damping.

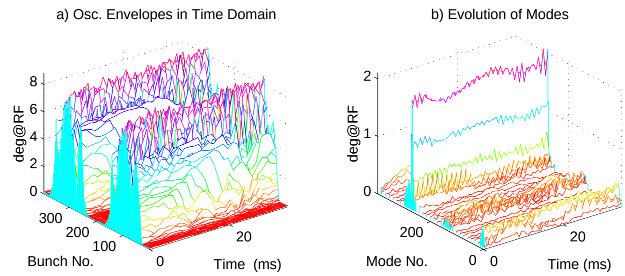

Figure 4: LFB data recorded with zero feedback gain at 390 mA. Shown are oscillation amplitudes versus bunch number (left) and versus mode number (right).

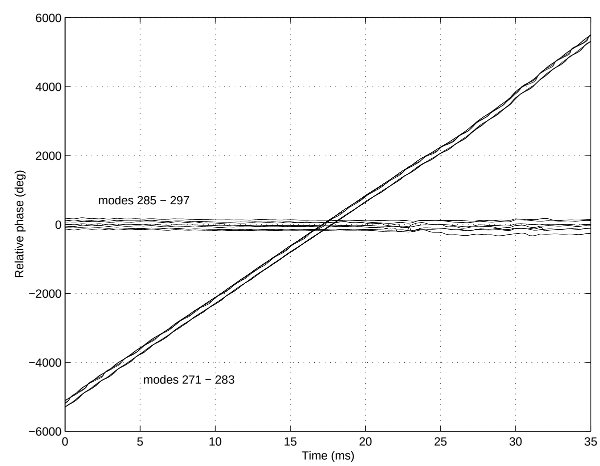

Figure 5: Time evolution of modal phases for multibunch modes selected from figure 4 (plotted relative to the phase of mode 299).

Pickup signals recorded with a digital oscilloscope [7] exhibit a phase advance between acjacent bunches of 0.24 rad, suggesting the excitation of multibunch mode 15 i.e. ± 19 MHz from the rf harmonics. The corresponding peaks are clearly visible in figure 2 and appear as “shoulders” of the 3 GHz line in figure 1. Strangly, this structure repeats itself every 125 MHz and creates the peaks around 2.89 GHz and 3.11 GHz. The exact periodicity suggests a 4-bucket modulation in the bunch pattern which was not observed otherwise. The driving impedance was never identified and may no have been a cavity HOM, since pickups inside the rf cavities showed no corresponding signal.

With the advent of the 3rd-harmonic cavities, the beam spectrum changed considerably. In particular, a 125 MHz periodicity was rarely observed. Figure 3 shows a scan from 3 GHz to 3.5 GHz, again with a 30 kHz span around each revolution harmonic. The most prominent excitation

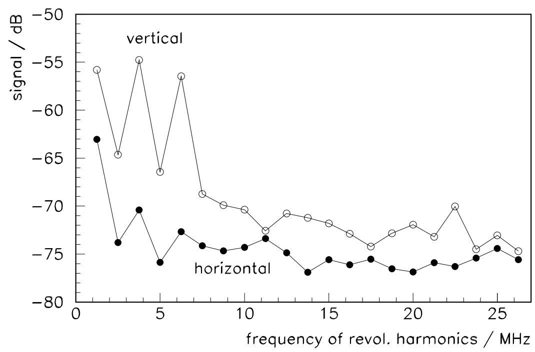

Figure 6: Amplitude of betatron sidebands at 300 mA as a function of the adjacent revolution harmonic frequency.

is observed around mode 280 i.e. $\pm$350 MHz from the rf harmonics. It is driven by a HOM at 2.35 GHz, and the LFB can only control the instability if this HOM is carefully tuned away from any revolution harmonic. In addition, there is a smaller excitation of unknown origin, spread over may revolution harmonics and centered slightly above mode 280. Its oscillation frequency is 0.8 kHz lower than that of the main excitation, indicating a difference in the imaginary parts of their driving impedances.

The presence of the second oscillation is also seen in LFB data, recorded with the feedback amplifier switched off. Figure 4 shows oscillation amplitudes as function of bunch number and mode number, and figure 5 shows the phase advance over time of selected modes. The technique of plotting modal phase space parameters, introduced by [6], is very sensitive to small differences of the imaginary part of impedances, and allows to tell whether the spread of an oscillation over different even-fill eigenmodes is due to the non-even fill pattern, or whether more than one driving impedance is involved. Figure 5 clearly shows two groups of modes evolving with different angular velocity.

The data shown here were taken at a beam current of 390 mA. Below 200 mA, only the narrow mode 280 excitation was detectable. Measurements with other fill patterns e.g. only one bunch train yielded similar results, except that two bunch trains of nearly equal spacing resemble one bunch train of double the revolution frequency. Thus, in the projection of the beam signal on even-fill modes, every other mode appears lower.

4 TRANSVERSE INSTABILITIES

It was known from the beginning that the vertical resistive-wall effect would be an issue for BESSY-II [8], whereas the onset of a horizontal resistive-wall instability is harder to predict for a flat vacuum chamber. Albeit more pronounced vertically, spontaneous betatron sidebands show up in both planes in the vicinity of the rf harmonics, which is consistent with the resistive-wall picture. Figure 6 shows their amplitude as a function of the adjacent revolution harmonic frequency at a beam current of 300 mA. As in the longitudinal case, every other sideband appears suppressed with a fill pattern of two bunch trains. Hardly any signal is observed more than 10 MHz away from the rf harmonics, and there is no clear evidence for any transverse instability other than driven by the resistive-wall impedance.

Transverse oscillations showed up only when the beam was longitudinally stable, either below 100 mA or after installation of the LFB. Raising the chromaticity of both planes cured the problem until the transverse feedback system was operational in December 1999 [4]. Since then, the chromaticities are reduced to $\xi_{x,y} \sim 1$ in order to optimize the dynamic aperture and thus the beam lifetime.

5 SUMMARY

A number of coupled-bunch instabilities were encountered in the BESSY-II storage ring. All of them are well controlled by feedback systems. In order to maintain beam stability in the future, multibunch oscillations are continuously under study using various techniques.

Longitudinally, there are several driving impedances of different characteristics, as shown above. Depending on the harmonic cavity tuning, other HOMs have been observed as well. The irregular fill pattern with two bunch gaps and synchronous phase transients due to the harmonic cavities add to the complexity of the picture.

Transversely, the resistive-wall interpretation appears to be valid, and no transverse HOMs were identified so far.

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