MEASUREMENT TECHNIQUES TO CHARACTERIZE INSTABILITIES CAUSED BY ELECTRON CLOUDS*

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Abstract

The study of electron cloud-related instabilities for the CESR-TA project has required developing new automatic and semi-automatic measurement techniques. The dynamics of the interaction of electron clouds with trains of bunches has been studied via three basic observations. Measurements of tune shifts of bunches along a train has been used extensively with the most recent observations permitting the excitation of single bunches within the train to avoid collective train motion from driving the ensemble of bunches. Another technique was developed to detect the coherent self-excited spectrum for each bunch within a train. This method is particularly useful when beam conditions are near the onset of an instability. The third method was designed to study bunches within the train in conditions before there is unstable motion. This is accomplished by separately driving each bunch within the train for several hundred turns and then observing the damping of its coherent motion. These last two techniques have been applied to study both transverse dipole (centroid) and head-tail motion. We report on the observation methods and give examples of typical results.

OVERVIEW OF THE MEASUREMENTS

The storage ring CESR has been configured as a test accelerator Cesr-TA to study electron cloud effects in the presence of trains of positron or electron bunches[1]. The electron cloud focuses the stored beam so the betatron tunes of bunches indicate the density of the cloud along the train. It can cause unstable motion in later bunches in the train, detectable by the amplitude of spectral lines at frequencies representing different modes of oscillation (e.g. dipole and head-tail) for bunches within the train. This interaction enlarges the vertical emittance, requiring vertical beam size measurements for each bunch. Instruments have been added or modified for the Cesr-TA program, including the bunch-by-bunch beam position monitor system (CBPM)[2], position detectors to measure the tunes and detect the internal modes of oscillation, vertical beam size monitors and beam kickers.

TUNE SHIFT ALONG THE TRAIN

Multi-bunch Large Amplitude Excitation

This method observes the tunes for all bunches when a ferrite magnet with a 2.5 msec pulse has uniformly excited transverse oscillations in the bunches within the train. The CBPM system is timed to read out a number of beam position monitors (BPMs) for a few thousand turns for all bunches; the data acquisition is synchronized with the triggering of the ferrite magnet's pulse. The turn-by-turn bunch positions are analyzed offline with a Fast Fourier transform (FFT) yielding the betatron tunes.

The data from all bunches is recorded simultaneously, making the acquisition relatively rapid for each set of conditions; thus this method is insensitive to drifts in the storage ring parameters. All bunches are driven at the same instant in the lowest coupled bunch mode for the train, and thus later bunches in the train are excited at the natural oscillation frequencies of earlier bunches, yielding multiple spectral peaks and confusing the identification of the later bunch's oscillation frequency. The beam's motion is fairly large compared to its size, e.g. the vertical oscillation amplitude may exceed several ten's of vertical sigma. (E.g. at 2.1 GeV the peak vertical beam displacement was 7 mm.) The beam's motion averages the tune shift over a large volume of the electron cloud.

Single Bunch Small Amplitude Excitation

A second approach measures bunch-by-bunch tunes with a reduced excitation from preceding bunches. This is accomplished by driving both of the horizontal and vertical stripline kickers using the external modulation input of the beam stabilizing feedback system to deflect only the bunch being studied. The signal for the external modulation port comes from a synthesizer, whose output frequency is swept with a 500 Hz saw-tooth, driving the bunch in the dipole oscillation modes when the excitation frequency crosses each betatron tune. Turn-by-turn data is recorded for all bunches for several BPMs using the CBPM system for a total number of turns sufficient to capture at least one excitation and damping cycle. This is repeated as the excitation's delay is stepped from one bunch to the next, yielding the positions of all bunches at each delay. The data is analyzed offline with a FFT to give the oscillation frequency of the excited bunch and the coupling of its motion to later bunches via the electron cloud. This method avoids driving the lowest train mode; it also yields bunch-to-bunch coupling from the electron cloud. This is slower than the preceding method as it acquires turn-by-turn position data for all bunches while each bunch is excited; it is sensitive to long-term drifts.

Feedback System Response

A third approach for tune measurements was apparent after installing the Dimtel[3] feedback electronics to damp

* Supported by US National Science Foundation (PHY-0734867) & Dept. of Energy (DE-FC02-08ER41538)
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bunches with spacings as small as 4 nsec. While looking at the FFT of the position for a single bunch as part of the feedback system diagnostics, it was observed that the signal response was a function of the feedback gain. At low gain the betatron peak is visible, but as the gain increases the amplitude of the peak decreases, becoming a notch in the spectrum at high gain. The explanation is that there is a broadband excitation of the beam and the feedback system is phased to preferentially suppress the bunch's response at the betatron frequency. When the feedback settings are fully optimized, the notch in the spectrum marks the location of the bunch's betatron oscillation frequency. This technique probes the electron cloud when the bunches are moving at small amplitudes, but it requires a fairly exact adjustment of the feedback parameters to clearly identify the notches in the spectra.

Self-Excitation

A fourth type of tune measurement is a by-product of the observation of beam instabilities (described in the next section) when the position signal of each bunch is measured with a spectrum analyzer. Two of the peaks that are visible in the self-excited spectra are the horizontal and vertical dipole modes. Since most of these measurements are taken in conditions when the beam is near an instability threshold for at least some of the bunches within the train, the amplitudes of the dipole motion will vary along the train. This method is sensitive to small amplitude oscillations of 0.4 mm-rms horizontally and 0.2 mm-rms vertically. Due to averaging, the one minute to acquire the spectra for each bunch leaves this method sensitive to any drifts in the storage ring.

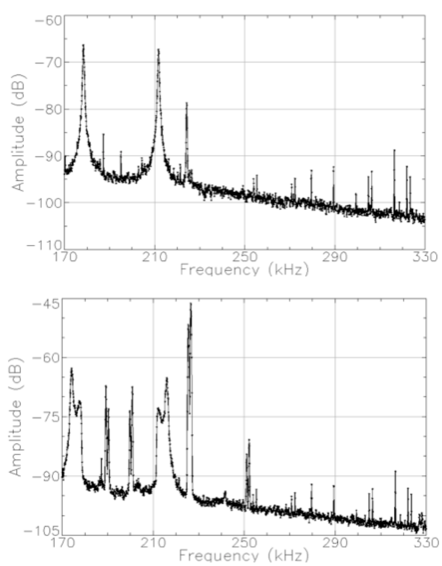

Figure 1: Self-excited beam power spectra for bunch 1 (top) & bunch 30 (bottom) in a positron train at 2.1 GeV.

MEASURING BEAM INSTABILITIES

Beam instabilities due to electron clouds are observed for bunches within the train by the growth of self-excited oscillations and vertical beam sizes of under various accelerator and cloud conditions. This method utilizes bunch-by-bunch beam position monitoring and an X-ray detector for determining vertical size of each bunch.

Bunch-by-bunch Position Spectra

Instabilities are detected bunch-by-bunch using a BPM detector connected to one of CESR's original relay-based BPM system processors. The signal is taken from one button, which is sensitive to both horizontal and vertical motion. The data taking software sets a trigger delay for the sampling gate in the processor, selecting a particular bunch within the train. This signal is then sent to the biased peak rectifier circuit, which has an effective bandwidth of 700 MHz and a decay time constant of approximately 5 msec. The resulting video signal is buffered and sent on a wideband coaxial cable to a spectrum analyzer in the control room. The spectrum analyze is operated in the baseband in its Narrowband Zoom mode. This mode of operation performs a ±20 kHz FFT on time slices of the signal and these spectra are averaged for 100 time slices, requiring 10 seconds for each of the four steps of the analyzer's center frequency.

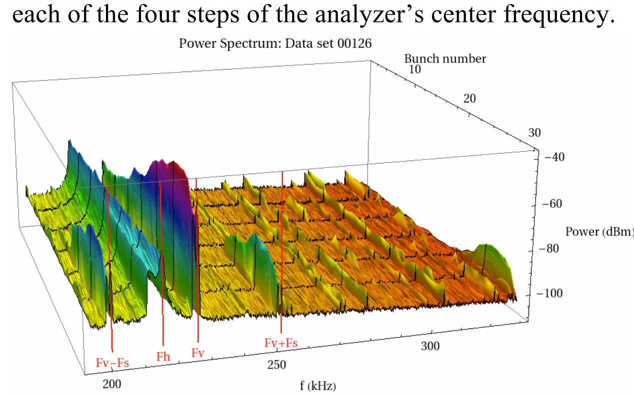

Figure 2: Self-excited beam position spectra for all 30 positron bunches in a train at 2.1 GeV. The horizontal axis is the frequency, the vertical axis is the spectral power and the third axis is the bunch number. (Bunch 30 is in the foreground.) Red lines locate the m = ±1 vertical head-tail lines, and the horizontal and vertical tunes.

Representative self-excited spectra of the first and last bunch in a 30-bunch positron train at 2.1 GeV are shown in figure 1. For this train the horizontal (vertical) tunes are in the range from 212 kHz to 218 kHz (224 kHz to 227 kHz.) The spectrum includes the ½-integer resonance at 195 kHz (becoming a reflection point for all peaks.) Additional lines are visible in the ranges 198-201 kHz and 250-252 kHz for bunch 30; these correspond to vertical head-tail modes at the vertical tune plus and minus the synchrotron oscillation frequency. The baseline is seen to fall as a 1/f noise spectrum. There are a number of unrelated noise lines throughout the spectra due to "cultural noise sources." A "mountain-range" plot of the spectra of all 30 bunches within this train is plotted in figure 2 for frequencies above 195 kHz. The self-excited vertical tune amplitudes begin to grow around bunch 10 and continue to grow in amplitude until bunch 20, where the two vertical head-tail lines first appear above the noise floor. Around bunch 15 the horizontal tune's peak begins to bifurcate. (This is also seen in the bottom plot of figure 1.) These data show the bifurcation of the vertical tune and head-tail lines for the last bunches in the train. In addition a number of "fences", i.e. peaks at fixed frequencies due to "cultural" noise are visible in figure 2.

Tests have examined the consistency and interpretation of the data. The vertical and horizontal tune peaks were identified by changing the beam tunes separately. The interpretation that the vertical head-tail lines are not inter-modulation products from the processing electronics was tested[5] by switching an attenuator into the signal upstream of the peak detector and observing that all dipole and head-tail spectral peaks decreased by 9±1 dB (rather than 18 dB for any inter-modulation products.) This method is fairly sensitive, but measurements take about one minute for each bunch and give the equilibrium state for unstable motion. With typical lifetimes, bunches must be refilled a few times for each set of conditions.

Bunch-by-Bunch Beam Size

A second instrument, used during the experiments to determine the vertical size of each bunch, is the X-ray beam size monitor[4]. Generally during the measurement cycle, beam size data are taken bunch-by-bunch and turn-by-turn immediately after the beam has been refilled.

MEASURING COHERENT MODE DAMPING RATES

Instability measurements record large amplitude signals as the bunches become unstable and their motion limits due to non-linearities. Observations of coherent damping describe the motion of bunches before they go unstable, the operational regime for storage rings.

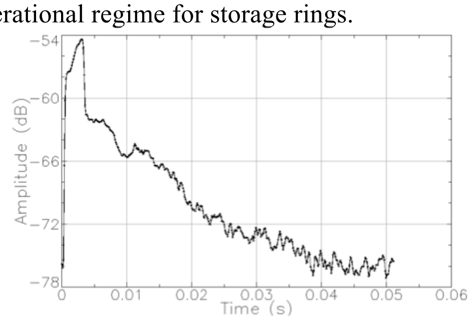

Figure 3: Drive-damp measurement: The trace is the response when one of the head-tail modes is excited.

Drive-Damp Excitation

This technique uses the same relay BPM configuration as the instability measurements. However, the spectrum analyzer's center frequency is adjusted to be at one of the frequencies corresponding to the vertical betatron dipole or a head-tail mode; the spectrum analyzer is also set to function as a tuned receiver, displaying signal amplitude vs. time. The spectrum analyzer's tracking generator's output is sent to the vertical feedback system's external modulation input. Digital timing controls for this external input adjust the delay for the excitation of only one bunch for spacings greater than 6 nsec. (For 4 nsec-spacings the timing of the pulse on the stripline kicker will slightly deflect a second bunch.) The drive-damp modulation of the beam is achieved by gating the spectrum analyzer's tracking generator signal off after the first 3 msec of the spectrum analyzer's sweep. The beam response grows to a saturated level during the driving impulse, then decays exponentially after the drive is switched off. (If the tracking generator's frequency is tuned away from the bunch's resonant frequency, the decaying response has oscillatory beats.) Small frequency adjustments of the excitation are needed to achieve fairly exponential decays.

For both betatron dipole mode and the head-tail mode measurements the spectrum analyzer drives the coherent mode frequency being measured. However, for head-tail modes one must also continuously drive the phase of the RF cavity at the synchrotron oscillation frequency. This produces a common longitudinal energy oscillation (about $\pm 7.6\mathrm{x}10^{-3}$) for all of the bunches within the train and, due to the RF system's non-linearities, increases the energy spread (and bunch length) of the bunches. For the head-tail modes the added energy spread, when taken with the deflecting field from the stripline kicker, deflects the lower energy particles in the bunch (moving toward the head of the bunch) more than the higher energy particles (moving toward the tail of the bunch.) Although this is a small differential effect, since the bunch is driven at one of the head-tail mode resonances, the head-tail oscillation amplitude builds up (as is seen in figure 3.) When the drive turns off, an initial 7 dB drop occurs as the off-resonance excitation of the dipole mode switches off; the roughly exponential shape thereafter is the head-tail mode's decay. (If the drive to the RF cavity's phase were removed, the head-tail mode signal would go away.) These data are useful for studying trains of bunches below the instability threshold, however again the acquisition takes about one minute per bunch.

CONCLUSIONS

This paper presents techniques for the beam dynamics observations at Cesr-TA using measurements of the tunes, the coherent mode amplitudes and damping rates and comments on strengths and weaknesses of the techniques.

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