TECHNIQUES FOR OBSERVING BEAM DYNAMICAL EFFECTS CAUSED BY THE PRESENCE OF ELECTRON CLOUDS*

M. Billing, G. Dugan, R. Meller, M. Palmer, G. Ramirez, J. Sikora, H. Williams, Cornell Laboratory for Accelerator-based Sciences and Education, Cornell University, Ithaca, NY, U.S.A.,
R. Holtzapple, California Polytechnic State University, San Luis Obispo, CA, U.S.A.

Abstract

During the last several years CESR has been studying the effects of electron clouds on stored beams in order to understand their impact on future linear-collider damping ring designs. One of the important issues is the way that the electron cloud alters the dynamics of bunches within the train. Techniques for observing the dynamical effects of beams interacting with the electron clouds have been developed. The methodology and examples of typical measurements are presented here.

OVERVIEW OF MEASUREMENT REQUIREMENTS

The storage ring CESR has been reconfigured and operates as a test accelerator Cesr-TA, studying the effects electron clouds in the presence of trains of positron or electron bunches[1]. With a 500 MHz RF acceleration system, CESR can store bunches with as little as a 2 nsec spacing, however for higher current operation the beam position monitor (CBPM) system and beam stabilizing feedback (BSF) systems are configured for bunches with at least a 4 nsec spacing. The most common bunch spacings employed during machine studies have been 4 nsec and 14 nsec, however higher multiples of 2 nsec spacing also have been utilized. The range of several Cesr-TA operating parameters are given in Table 1.

Table 1: Cesr-TA Operating Parameters

Parameter	**Typical Range**	**Units**
Beam Energy	2.0 - 5.3	GeV
Circulation Time	2.56×10^{-6}	sec
Number of Superconducting (SC) Wiggler Magnets	0 - 12	
Horizontal Emittance	1×10^{-6}	m-rad
Bunch Spacing	4, 6, 8, 10, 12, 14, …	
Maximum Bunch Charge	25.6	nC
Maximum Single Beam Current	3 – 200 (depending on beam species and powering of SC wigglers)	mA

There are several beam parameters, which are particularly relevant for the study of electron cloud effects. Since the electron cloud can produce focusing of the stored beam, measuring the betatron tunes of bunches through the train gives information about the density of the cloud along the length of the train. The electron cloud can also produce unstable motion in bunches later in the train. To observe the unstable motion, it is necessary to detect the amplitude of the betatron frequency and any other frequencies representing different modes of oscillation (e.g. head-tail modes) of bunches within the train. The unstable motion may also result in enlargement of the vertical beam size, so the measurement of the vertical beam size for each bunch in the train is important.

MEASUREMENT HARDWARE

Several instruments have been added or modified for use with the CESR-TA program. They include the bunch-by-bunch beam position monitors, position detectors, which measure the tunes and detect some of the internal modes of oscillation, vertical beam size monitors and beam kickers.

Beam Position Monitors

During the Cesr-TA project the beam position monitoring system underwent an upgrade throughout the entire storage ring. The new CBPM system[2] has independent processing electronic readout modules at or near each of the quadrupole magnets, which can measure the position of every bunch, spaced by as little as 4 nsec, with better than 10 μm turn-by-turn resolution. As shown in figure 1, each module incorporates four front end boards with dual parallel 16-bit digitizer chains based on the Analog Devices AD9461 operating at digitization rates of 125 MHz. When operating with 4 nsec-spaced bunch trains, digitizing is interleaved between the two chains while, for times when CESR operates for synchrotron light users with dual species of 14 nsec-spaced bunches, each digitizer chain handles either the electron or positron bunches. The front-end boards have both a fixed gain amplifier optimized for precision measurements for bunches with approximately 1×10^{10} particles per bunch and a digital variable gain amplifier for measurements over a wide dynamic range. The triggering and timing configurations are carried out by a dedicated timing board integral to each module. This board takes a turn marker signal from the CESR master timing system and provides overall digitization rate control, adjustment capability for channel-to-channel digitization times, and global adjustment capability for the module digitization time

---

* Work supported by the US National Science Foundation (PHY- 0734867) and Department of Energy (DE-FC02-08ER41538)

relative to the bunch arrival time at the detector. This fine degree of local timing adjustment is required in order to maintain the resolution and noise performance of each device. Communications, operational control, and onboard data processing for each device is provided through a digital board and its TigerSharcß digital signal processor (DSP). Communications are by both Ethernet and a dedicated CESR field bus.

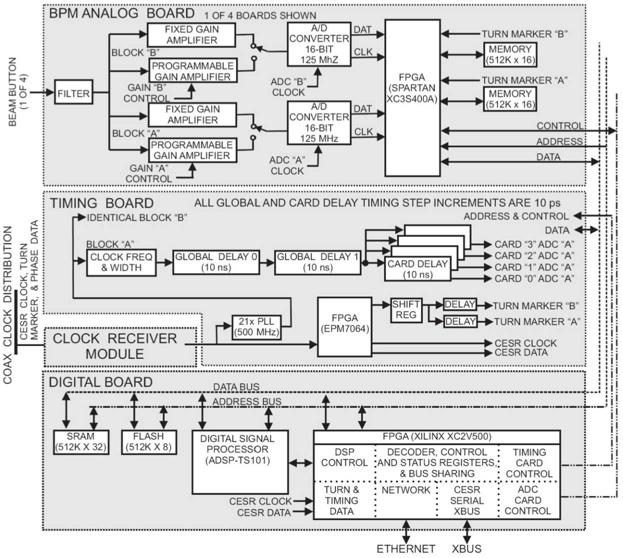


Figure 1: Functional diagram of the CBPM module.

Tune and Motion Detector

The variation of the tunes of individual bunches carries information about the global electron cloud density. Different methods have been employed to measure the tunes of the bunches during the beam dynamics studies.

A simple method for determining the tunes for each bunch in a train of bunches is to use a subset of the complete number of CBPM modules to measure the beam position turn-by-turn for each bunch. The block diagram for this configuration is shown in figure 2a. The data is read out from the CBPM modules and written into a raw data file. Each BPM's position data is then analyzed offline by performing a Fourier transform, which yields the spectral lines of the beam's transverse motion. This method is most often used in conjunction with a kicker that deflects all of the bunches within the train.

A second method is shown in the block diagram in figure 2b. This detection method makes use of a few BPM detectors, which are still connected to CESR's original relay-based BPM system processors. The signal from one BPM button is routed via coaxial relays to one of the analog processors, where fixed gain amplifiers and/or attenuators may be inserted in the signal path to maintain the peak signal level within a factor of five over a wide range of currents. After the gain adjustment the signal passes on to an RF gating circuit, which is triggered by the Fast Timing System, allowing the selection of the signal from a single bunch, sending it to a peak rectifier circuit (with approximately 700 MHz bandwidth) and then routing its output video to a spectrum analyzer in the Control Room. In top plot of figure 3 the timing aperture for the gating circuit was measured by sweeping the gate delay for the signal coming from a single bunch to observe the signal amplitude vs. gate delay. A second method for observing the signal crosstalk between bunches is seen in the bottom plot of figure 3. This plot is obtained by shaking the beam vertically and observing the spectrum analyzer's signal amplitude as a function of gate delay. This second observation gives the base timing aperture as 7.5 nsec wide, giving more than 20 dB isolation of the signal crosstalk from adjacent 4 nsec-spaced bunches and a signal isolation of greater than 50 dB for 14 nsec-spaced bunches.

The initial setup of the storage ring parameters for the tune measurements is performed with a single stored bunch. The betatron tune instrumentation configuration, capable of detecting the beam's tune in both planes, is shown in the block diagram in figure 2c. In this mode the single bunch is excited with the relatively narrow bandwidth shaker magnets (described below) and detected with a swept spectrum analyzer.

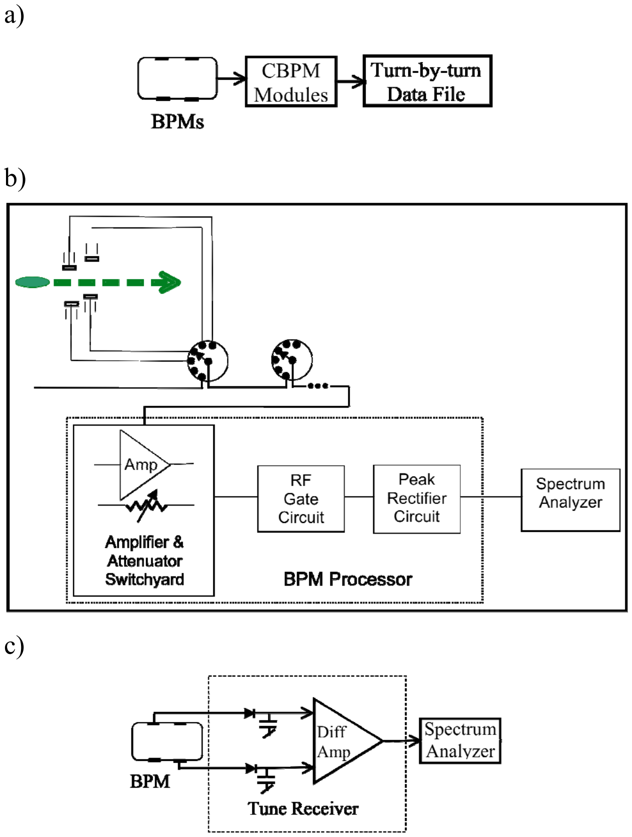


Figure 2: Block diagrams for three different betatron tune receiver configurations: a) Utilizing the bunch-by-bunch and turn-by-turn readout capabilities of the CBPM system. b) Relay BPM system able to gate on a single bunch's BPM signal. c) Simple block diagram of a narrow-band tune receiver, shown in the mode where it can detect both the horizontal and vertical betatron tunes.

Beam Excitation

To measure the tune spectra of bunches it is necessary to observe them undergoing coherent motion. In some cases their self-excitation is sufficient for a good tune measurement, but in other cases the beam must be driven with some type of dipole kicker. There are three types of dipole kickers used in CESR for the measurements described here.

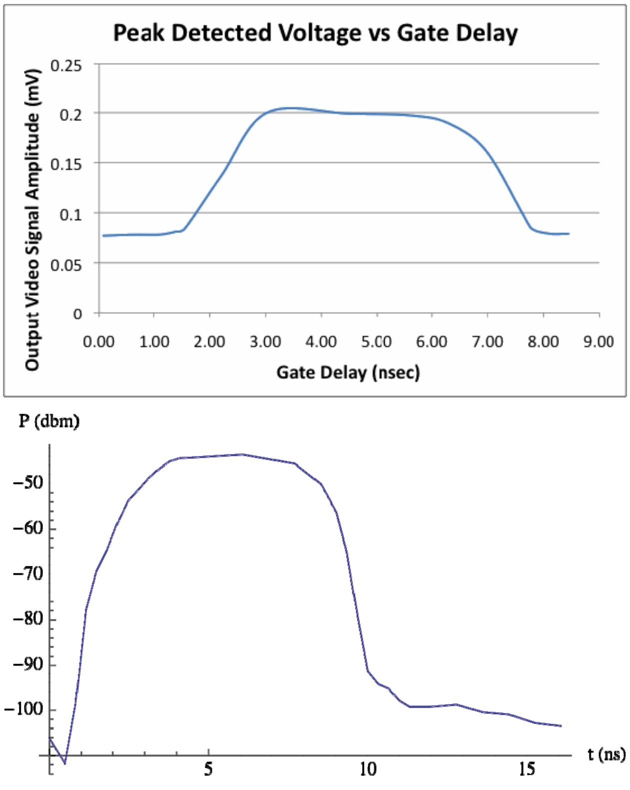


Figure 3: Relay BPM processor's gate timing aperture as measured (Top) with the video signal in the Control Room showing a 77 mV DC offset from its peak rectifier circuit and (Bottom) by driving a single bunch vertically and measuring its response vs. gate delay.

One type of kicker is called a pinger magnet and it is used for single impulse deflection for the beam. There are three pingers installed in CESR: two are horizontal and one is vertical. A horizontal pinger is shown in figure 4 as a single-turn ferrite-core pulsed magnet, which surrounds a Kovar-coated ceramic vacuum chamber. The horizontal pingers are excited using a thryatron with a approximately square pulse, having a flattop region about a 2 µsec long. This is more than long enough to deflect all bunches in one train with the same angle. The pulse shape for the vertical pinger has a different waveform; the magnet is driven with a half sine-wave pulse of approximately 2.5 µsec duration. The pingers can be triggered via CESR's Fast Timing System at repetition rates as high as 60 Hz and the triggers can be synchronized with the CBPM turn-by-turn and bunch-by-bunch data acquisition. Because of its half sine-wave shape, the vertical pinger is timed to have the train of bunches arrive straddling the peak of its deflection.

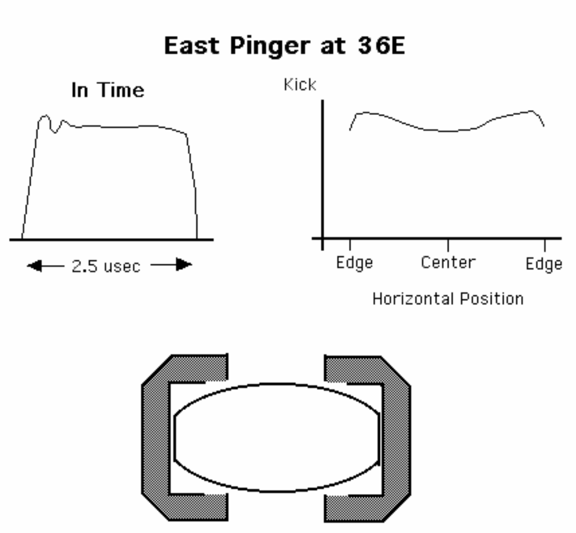


Figure 4: Horizontal pinger. This is a pulsed ferrite magnet surrounding a metalized coated ceramic vacuum chamber, which provides deflection to the beam with a single turn's duration.

The second type of deflection element, utilized for beam dynamics measurements, is a stripline kicker, an example of which is shown in figure 5. There are two (one horizontal and one vertical) stripline kickers installed in CESR. They are the deflectors for the transverse dipole bunch-by-bunch BSF systems for the ring. They have a 3.5 nsec long transit time and are excited with 250W 250 MHz RF amplifiers. As a part of the transverse feedback system for 14 nsec-spaced bunches, the amplifiers are modulated with 14 nsec single period sine-wave, producing a "constant" (±5%) deflection to the beam for about 1 nsec. Each feedback system modulator has an external modulation input and when it is enabled, the input will allow the deflection of any combination of 14 nsec-spaced bunches. For beam dynamics measurements, the stripline kickers are most often used to deflect individual bunches within the train.

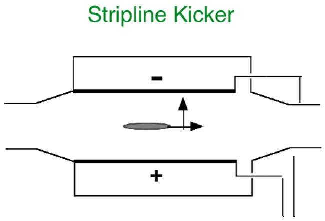
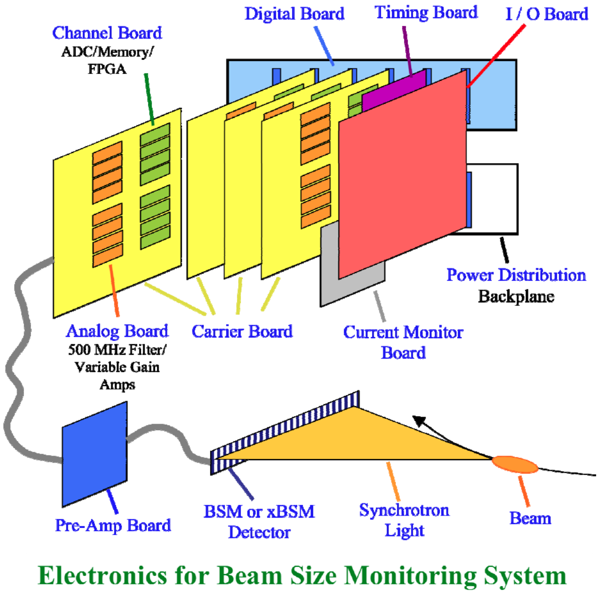


Figure 5: Stripline kicker, having two plates that are driven differentially to deflect the bunch.

For completeness we will mention a third type of deflection component in the storage ring. This is low-frequency shaker magnet, a multi-turn coil wound around a H-frame ferrite core surrounding a metalized coated ceramic vacuum chamber. Although this shaker magnet is not in use during beam dynamics measurements, since it is unable to distinguish motion of individual bunches, it is important for the detection of the tunes as conditions are re-established at the beginning of each measurement period.



Electronics for Beam Size Monitoring System

Figure 6: Mechanical layout for the 4 nsec X-ray beam size monitor and its readout electronics

Beam Size Measurement

To study the growth of the vertical beam size due the electron cloud, CESR has installed X-ray beam size monitors (xBSM) on CHESS beam lines for both electron and positron beams. Described elsewhere in detail[3], these detectors consist of upstream X-ray optics configurable as an adjustable slit (AKA a pinhole), a Fresnel zone plate optics chip and a coded aperture optic chip, any of which may be moved into the X-ray beam emanating from one of the hardbend dipole magnets in CESR. A mechanical block diagram of the xBSM system is visible in figure 6. After passing through the X-ray optics, the X-ray beam illuminates a vertical-oriented 32-channel linear pixel detector array having a 50 µm pitch. The detector is capable of measuring the signal from bunches spaced as closely as 4 nsec. After passing through a pre-amplifier, the bunch-by-bunch signals for the 32 channels are digitized and can be recorded turn-by-turn. Utilizing the same timing hardware as the CBPM modules, the xBSM system can be triggered synchronously with the CBPM modules allowing for turn-by-turn beam size measurements correlated between the two systems. The analysis of the xBSM data yields vertical centroid position of the bunch and the vertical beam size for each bunch on each turn.

SCOPE OF BEAM DYNAMICS STUDIES

The beam dynamics studies have focused attention on three specific types of measurements. The first of these is the measurement of the betatron dipole-mode tunes for the bunches within the train, yielding information about the electron cloud density build-up along the train via the localized focusing effect of the cloud on the stored beam. The second class of measurements is associated with determining the onset of unstable motion for stored bunches within the train. The development of the dynamical effects along the train are observed for each bunch using a BPM to detect the spectral composition of centroid motion and the bunch-by-bunch and turn-by-turn xBSM to characterize any vertical beam size enlargement. This set of observations identifies the number of the bunch within the train, at which the unstable motion begins and the rate of growth of the instability. A third set of measurements allows the examination along the train of the damping rates for individual bunches of dipole and head-tail transverse modes below the onset of unstable motion. The measurement techniques, developed for Cesr-TA, will be described in the next three sections.

As part of the beam dynamics measurements, it is necessary to vary the beam conditions. In CESR the spacing and number of bunches within trains can be arranged with great flexibility. The most common spacings are 4 nsec and 14 nsec, but any multiple of 2 nsec greater than 4 nsec is possible. During operation of the storage ring, longitudinal and transverse bunch-by-bunch BSF may be employed.

TUNE SHIFT ALONG THE TRAIN

Over the Cesr-TA project several different techniques have been utilized for making tune shift measurements for individual bunches within trains of bunches. These techniques, their benefits and limitations will be described in the following subsections.

Multi-bunch Large Amplitude Excitation

This method for observing the tunes of different bunches within the train pulses a pinger magnet with a single-turn excitation to deflect all of the bunches within the train and thus start an oscillation of their centroids. The CBPM system is then is timed to read out a number of BPMs over several thousand turns for all bunches in the train (see block diagram in figure 2a); the data acquisition is synchronized with the triggering of the pinger magnet's deflection. After recording the turn-by-turn bunch positions, the data is analyzed offline with a Fast Fourier transform (FFT), from which the betatron tunes are determined. During these measurements the peak vertical beam displacements, for example, were typically 7 mm and 2 mm at 2.1 GeV and 5.3 GeV, respectively.

Since data from all bunches is recorded at the same time, it is relatively rapid to take data in one set of conditions and, since the data from all bunches is taken on the same turns, this method is relatively insensitive to any drifts in the storage ring tunes. However, the fact that all bunches are excited at the same instant implies that the lowest coupled bunch mode is excited for the train of bunches. This makes later bunches in the train susceptible to being excited at the natural oscillation frequencies of preceding bunches, producing multiple spectral peaks in close proximity and confusing the identification of the later bunch's oscillation frequency. It is also the case that the pinger excitations are relatively large with respect to the stored beam's size, e.g. typically the vertical oscillation amplitude may exceed many ten's of the vertical sigma. So the beam's oscillation is exploring a fairly large volume of the electron cloud's distribution.

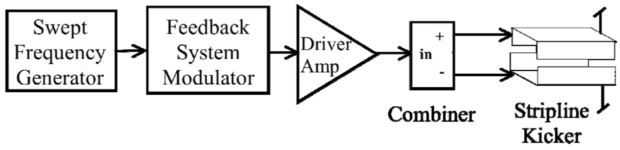


Figure 7: Single bunch excitation method using the stripline kicker, driven by a swept frequency source via the feedback system's external modulation port.

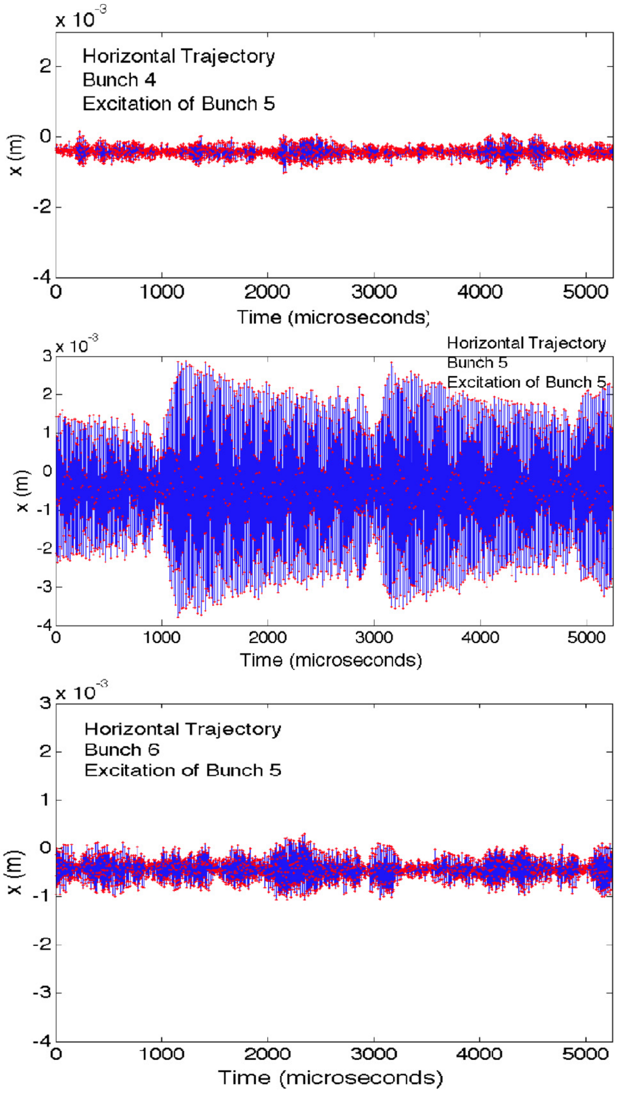


Figure 8: Horizontal position of bunches 1, 5 and 10 (respectively for the top, middle and bottom plots) for a 10-bunch train when only bunch number 5 was driven.

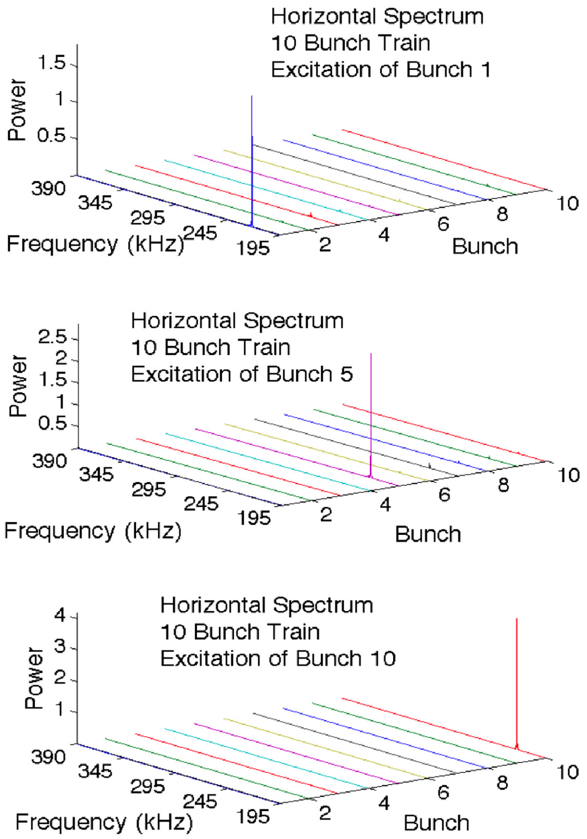


Figure 9: Horizontal position spectra of all bunches in a 10-bunch train when bunches number 1, 5 and 10 (respectively for the top, middle and bottom plots) were driven individually.

Single Bunch Small Amplitude Excitation

Another approach has been developed for bunch-by-bunch tune measurements. This approach focuses on reducing the coupling from preceding bunches to the bunch that one is trying to measure. As shown schematically for one stripline kicker in figure 7, this is accomplished by driving both the horizontal and vertical stripline kickers only for the bunch being measured by making use of the external modulation input for the BSF system. The source for the signal for the external modulation port comes from a frequency synthesizer, whose output frequency is swept across the range of betatron oscillation frequencies for the bunches. The frequency is swept with a saw-tooth at 500 Hz, driving the bunch in the dipole oscillation mode when the excitation frequency crosses the betatron resonance. Again the turn-by-turn position data is recorded for a number of BPMs using the CBPM system readout (as shown in the block diagram in figure 2a) with the total turn record length long enough to capture at least one excitation and damping cycle. The measurement process is repeated as the excitation's delay is stepped from one bunch to the next, resulting a set of positions for all bunches at each delay. The data is analyzed offline with a FFT to give the oscillation frequency of the excited bunch and coupling of its motion to subsequent bunches via the electron cloud.

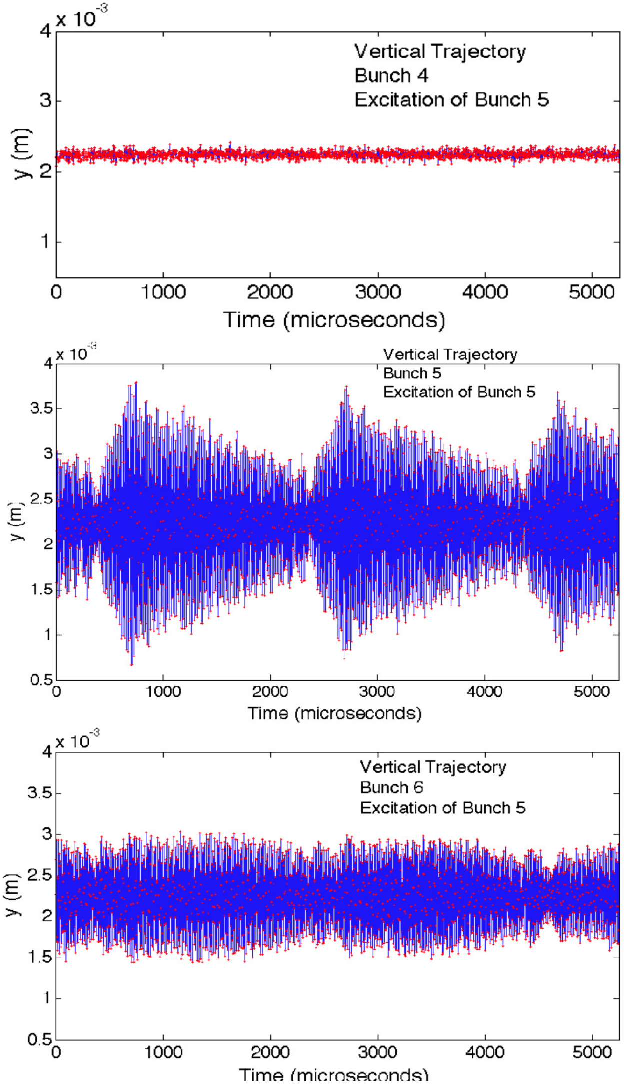


Figure 10: Vertical position of bunches 1, 5 and 10 (respectively for the top, middle and bottom plots) for a 10-bunch train when only bunch number 5 was driven.

Some results are presented here for illustration of this technique; the data were taken with a 10 bunch train with a 14 nsec spacing in 2.1 GeV conditions. Figure 8 shows the horizontal position data for the first, fifth and tenth bunch, when only bunch number 5 was being excited. During the 2048-turns of the data-samples taken on simultaneous turns for the three bunches, it is clear that bunch 5 was excited with two complete cycles of the swept signal source. This is even clearer in figure 9 when viewing the horizontal spectra of all 10 bunches when bunch numbers 1, 5 and 10 were being driven individually. The fact that the stripline kicker is exciting only one bunch is quite evident in both figures 8 and 9.

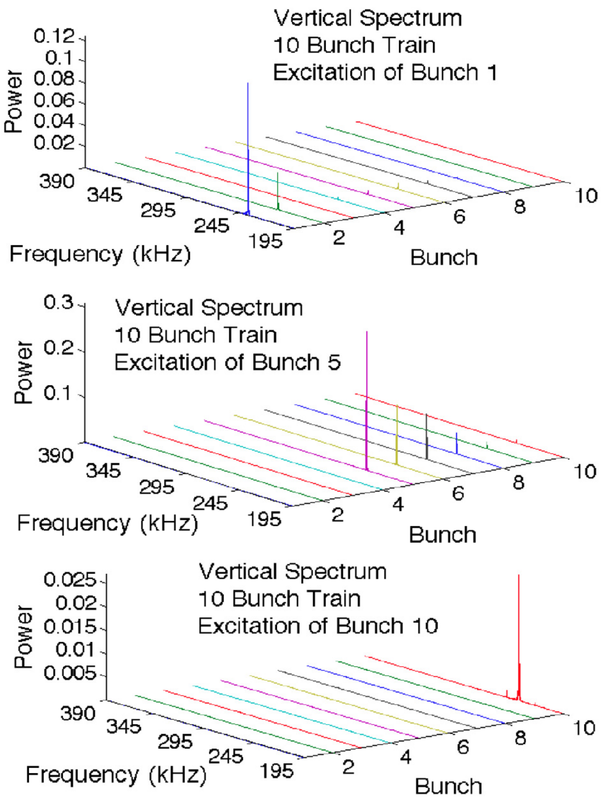


Figure 11: Vertical position spectra of all bunches in a 10-bunch train when bunches number 1, 5 and 10 (respectively for the top, middle and bottom plots) were driven individually.

For comparison with the horizontal data, the matching set of vertical data is presented here for the same storage ring and electron cloud conditions as above. The vertical position data for bunches 1, 5 and 10 is shown in figure 10, when only bunch 5 is driven. Also the vertical spectra for all bunches are shown in figure 11, when bunches 1, 5 and 10 are individually excited. The interesting feature, visible in the vertical data, is that even though only one bunch is being driven, its motion is coupling the subsequent bunches in the train. Figure 11 presents evidence that this coupling increases along the train, suggesting that the electron cloud may be playing some part in this bunch-to-bunch vertical dipole coupling.

This technique has the advantage of avoiding cross-coupling from preceding bunches to the bunch being studied, while also providing information about the coupling of the motion of one bunch to later bunches via the electron cloud. The excitation level can, in principle, be tailored for the bunch that is being driven; the ability to keep a relatively fixed amplitude for the bunch's oscillation could be important for conditions when the first bunches in the train are more stable but the latter bunches are not. This method has the drawback that it slower that the preceding method as it requires collecting turn-by-turn position data for every bunch times the number of bunches within the train, and is, therefore, sensitive to drifts in the tunes of the storage ring.

Feedback System Response

Another approach for tune measurements became apparent after the installation of the Dimtel[4] feedback electronics, capable of damping bunches with spacings down to 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 varied as a function of the feedback gain. At low gains the betatron peak is visible, but as the gain is increased the amplitude of the peak decreases until it become a notch in the spectrum at high gain. The explanation for this effect is that there is a broadband excitation of the beam and the feedback system is phased to suppress the bunch's response preferentially at the betatron frequency. When the feedback settings have been fully optimized, the notch in the spectrum for each bunch marks the location of its betatron oscillation frequency.

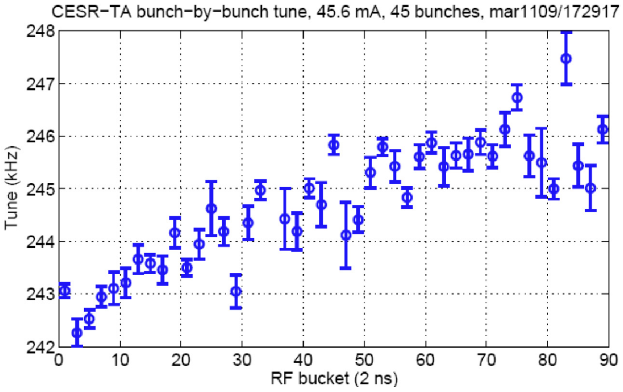


Figure 12: Vertical tune vs. RF bucket number for a train of 45 bunches with 4 nsec bunch spacing determined from notches in the spectra from the feedback error signal.

The position data generally represents the effect of probing the electron cloud in a regime when the bunches are moving at small amplitudes. An example of data taken using this method is seen in figure 12. There is a very clear trend for the vertical focusing effect from the accumulating electron cloud, which is visible the plot. Although this method is quite appealing, only a few tune shift measurements have been performed via this method. This technique works well for 4 nsec-spaced bunches, but it requires fairly exact adjustments of the feedback system parameters to be able to clearly identify the notches in the bunch spectra. To obtain the most accurate spectra, the data for each bunch is averaged typically for 30 seconds, allowing some uncertainty in the tunes due to longer–term drifts in the storage ring focusing.

Self-Excitation

The last method for bunch-by-bunch tune shift measurements to be presented here is a by-product of the observation of beam instabilities, described in the next section. In this set of measurements the position spectrum of each bunch is measured with a spectrum analyzer. Two of the peaks that are visible in these self-excited spectra are the horizontal and vertical dipole modes. The shift of the tunes from bunch to bunch are easily detected via this method. Since most of these measurements are taken in conditions when the beam is above or near an instability threshold for at least some of the bunches within the train, the self-excited amplitudes of the dipole motion will vary along the train. This method is quite sensitive to low signal levels with the noise floor for small amplitude oscillations at the level of 0.4 μm-rms horizontally and 0.2 μm-rms vertically. Due to averaging in the spectrum analyzer, the data acquisition requires about 1 minute for each bunch, leaving this method sensitive to drifts in the storage ring tunes.

MEASURING BEAM INSTABILITIES

An important set of Cesr-TA measurements study beam instabilities due to the electron cloud. This study focuses on the growth of self-excited oscillations of the bunch's centroid and the growth of vertical beam size along the train under various accelerator and electron cloud conditions. The first part of the hardware utilized for these measurements is a monitor for the bunch-by-bunch beam position. The other detection system required is the xBSM monitor for determining vertical beam of each bunch.

Bunch-by-bunch Position Spectra

For instability studies the bunch-by-bunch position measurements are accomplished by a BPM detector connected to one of CESR's original relay-based BPM system processors, which in turn passes its video output signal to a spectrum analyzer in the control room. (For further description see text above and the block diagram shown in figure 2b.) BPM33W, which is located at a higher vertical beta point, has generally been used as the detector for these observations. The signal is taken from one button, making it sensitive to both the horizontal and vertical motion. The data taking software sets the trigger delay for the sampling gate to select a particular bunch within the train. For almost all of the data, an RG-174 coaxial cable is placed within the signal path to limit the bandwidth of the button signal (giving an effective 20 dB of signal attenuation) and to this an additional 12 dB of amplification is added. The 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 10 nsec. The resulting video signal is buffered and sent on a wideband coaxial cable to a spectrum analyzer in the control room.

The spectrum analyzer is an Hewlett Packard model 3588A, operating in the baseband (in these studies the center frequency ranges from 190 kHz to 210 kHz) in Narrowband Zoom mode with a 40 kHz span. This mode of operation performs a ±20 kHz FFT on time slices of the signal and these spectra are averaged for 100 time slices, taking about 10 seconds for each 40 kHz step of the center frequency. At 2.1 GeV the position sensitivity of the signal from the BPM at 33W was measured to be

$$x_{rms} = x_0 \left(\frac{1\ \text{mA}}{I_b}\right) 10^{A_x/20\ \text{dBm}} \qquad y_{rms} = y_0 \left(\frac{1\ \text{mA}}{I_b}\right) 10^{A_y/20\ \text{dBm}}$$

where $x_0 = 81.3$ mm and $y_0 = 45.3$ mm. With this gain configuration and over the frequency range of study, the noise baseline falls from -95 dBm to -105 dBm (corresponding in the vertical direction, respectively, to displacements of 1.1 µm-rms to 0.33 µm-rms for a 1 mA bunch.)

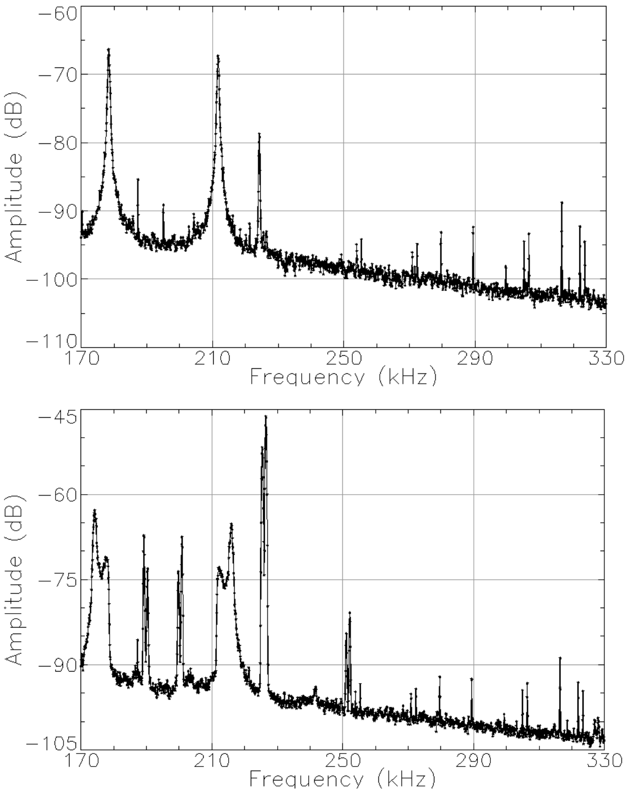


Figure 13: Self-excited beam power spectra for bunch 1 (top) and bunch 30 (bottom) in a 30 bunch-long positron train at 2.1 GeV.

Representative self-excited spectra of the first and last bunch in a 30-bunch positron train at 2.1 GeV are shown in figure 13. For this train the horizontal tunes are in the range from 212 kHz to 218 kHz, and the vertical tunes are in the range from 224 kHz to 227 kHz. Since this spectrum overlaps the ½-integer resonance at 195 kHz, this frequency is a reflection point for the spectra. For bunch 30, additional lines are visible in the ranges 198-201 kHz and 250-252 kHz; these correspond to vertical head-tail modes as their frequencies are plus and minus the synchrotron oscillation frequency added to the vertical tune. The baseline is seen to be falling as roughly a 1/f noise spectrum. There are also a number of unrelated noise lines, scattered throughout the spectra assumed to be due to "cultural noise sources." A "mountain-range" plot of the spectra of all 30 bunches within a 30 bunch-long train is plotted in figure 14. A cut of the spectrum has been made at the half integer resonance (195 kHz) to suppress the "reflected" spectral lines. In this plot the self-excited vertical tune amplitude begins to grow at approximately bunch 10 and continues to grow in amplitude until near bunch 20. In this region the two vertical head-tail lines appear above the noise background. Also around bunch 15 the spectral peak of the horizontal tune appears to bifurcate, something which is also seen in the bottom plot of figure 13, and on close examination these data also show bifurcation of the vertical tune and the vertical head-tail lines for the latest bunches in the train. Figure 14 also shows a number of "fences", i.e. peaks in the spectrum at fixed frequencies due to external "cultural" noise sources.

Many tests have examined the self-consistency and interpretation of the data. The identification of the vertical and horizontal tunes was checked by changing the controls for each separately and verifying which spectral peak moved. They were also checked using BPMs at other locations, which had buttons summed to produce dominantly horizontally- or vertically-sensitive detectors. The interpretation that the vertical head-tail lines were not inter-modulation distortion components coming from the processing electronics was tested [5] by switching an attenuator into the signal path upstream of the peak detector and observing that all spectral peaks decreased by 9±1 dB. If the head-tail lines were actually inter-modulation cross-products from the non-linearity of the electronic processing, then they would have decreased by 18 dB and they only decreased by 9 dB.

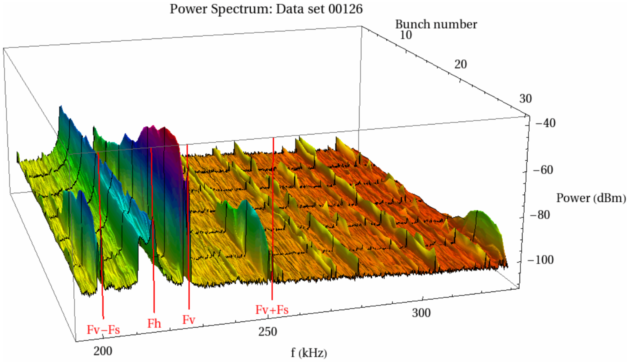


Figure 14: Self-excited beam power spectra for bunches 1 through 30 in a 30 bunch-long positron train at 2.1 GeV. The horizontal axis is the frequency, the vertical axis is the spectral power in dB and the axis into the page is the bunch number with bunch 30 being in the foreground. Red vertical lines in the foreground denote in ascending order the location of the m = -1 vertical head-tail line, the horizontal tune, the vertical tune and the m = +1 vertical head tail line.

This method for detecting the frequency spectra of the bunches is fairly sensitive, however measurements must be made for each individual bunch. The measurement time is about 1 minute per bunch for the frequency range, over which we choose to take data. This means that the data represents the equilibrium state of any unstable motion. It also implies that due the typical beam lifetimes, the beam must be refilled a number of times during the set of data for one observation. In our case we choose typically to refill after measuring five bunch spectra, which, when plotted, gives the amplitude of peaks within the spectrum a slightly scalloped shaped over five bunches. This refilling cycle coordinates fairly well with the cycle to measure and readout the bunch-by-bunch and turn-by-turn xBSM data.

We have tried to readout the turn-by-turn and bunch-by-bunch positions from a number of BPMs via the CBPM system (giving a much faster data acquisition time.) Unfortunately the head-tail lines are not visible in the CBPM data. Our explanation is that the relay BPM system peak rectifies the position signal and, if there is a temporal variation due to synchrotron motion, the arrival time of the signal varies correspondingly. This gives a frequency modulation to the position signal when viewed by the spectrum analyzer. The CBPM processing is different; the signal is sampled at a fixed time corresponding to the positive peak of the button BPM pulse. Any variation in the arrival time produces only a second order variation in amplitude and, even if one moved the sampling time significantly off of the peak, it does not produce any signal at the head-tail line frequencies.

Bunch-by-Bunch Beam Size

The second detection system in use during these experiments for determining vertical beam size of each bunch is the xBSM monitor (described above with its block diagram in figure 6). The hardware for the xBSM system is explained in greater detail elsewhere[3]. During a given set of instability measurements typically data are taken using all three sets of optics, the adjustable slit (AKA pinhole), the Fresnel zone plate optics chip and the coded aperture optic chip. This allows the greatest range of sensitivity for measurements of the vertical size and centroid motion of the beam. During the measurement cycle, the beam size data are taken bunch-by-bunch and turn-by-turn generally immediately after the train has been topped off, usually occurring after taking the spectrum for every fifth bunch.

MEASURING COHERENT MODE DAMPING RATES

A complement to the instability measurements, described in the preceding section, are the damping rate measurements for the coherent transverse modes. The instability measurements easily record the large amplitude signals as the bunches become unstable and ultimately limit due to non-linearities in the bunch's dynamics. However, the damping measurements give information about the stability of the bunch at small amplitudes before the bunch goes unstable, the regime in which storage rings and damping rings will actually operate. These studies will give some insight about how the beam instability begins developing as one looks from bunch to bunch along the train.

Drive-Damp Excitation

The basic idea for these observations is to employ the same relay BPM configuration as is used for the instability measurements. However, the spectrum analyzer's center frequency is adjusted to be at either the vertical betatron dipole-mode frequency or one of the head-tail mode frequencies while the spectrum analyzer is set to be in Zero Span mode. In this mode the analyzer functions as a tuned receiver with its display producing signal amplitude vs. time. The spectrum analyzer's tracking generator's output is sent to the vertical feedback system's external modulation input. Aside from the spectrum analyzer's control settings, this is quite similar to the hardware configuration shown in figure 7. By adjusting the digital timing controls for the modulator's external input, it possible to drive only one bunch as long as bunch spacing is greater than 6 nsec. (If the bunch spacing is 4 nsec, then the timing of the pulse on the BSF system's stripline kicker will the deflect the bunch under study and slightly kick the following bunch.) To permit the drive-damp modulation of the beam, there is one additional element added to figure 7's block diagram. This element is a modulating gate for the spectrum analyzer's tracking generator signal. This modulator gate is timed with the spectrum analyzer's timing sweep to pass the tracking generator output for 3 msec at the beginning of the sweep and then to gate off its output until the start of the next sweep.

An illustration of the timing and the expected signal response are shown in figure 15. The red curve shows that the amplitude of the transverse excitation of the bunch vs. time is an impulse. The expected beam response initially grows during the driving impulse, usually reaching a saturated level, and then decays exponentially after the drive is switched off (shown in the logarithmic plot as a linear decrease vs. time.) If the spectrum analyzer's tracking generator's frequency is tuned away from the bunch's resonant frequency, the decaying response will have periodic oscillatory beats. So during the measurement it is necessary to make small tuning adjustments to the excitation frequency to produce the most exponential decay possible.

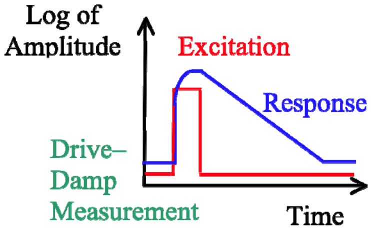


Figure 15: Illustration of the drive-damp measurement: The red trace is the amplitude of the excitation driving the bunch. The blue trace is the bunch's response.

The excitation of the bunch is accomplished in a somewhat different manner for the betatron dipole mode and the head-tail modes. In the both cases the spectrum analyzer is set to drive the coherent mode frequency being measured. However, for the head-tail modes it is necessary to also continuously drive the external modulation input for RF cavity phase at the synchrotron oscillation frequency. This imposes a longitudinal energy oscillation on all of the bunches within the train, causing them to uniformly shift their arrival times and displace the train's centroid horizontally proportional to the storage ring's dispersion. The typical amplitude of this oscillation is relatively large, with the peak fractional energy varying as much as $\pm 7.6 \times 10^{-3}$. One explanation of the driving mechanism for head-tail modes is that with a constant deflecting field in the stripline kicker, the energy oscillation causes the head of the bunch (at lower energy) to be deflected more than the tail of the bunch (at higher energy.) Although this is a fairly small differential effect, the bunch is being driven on the head-tail resonance allowing the oscillation amplitude to build up.

Two examples of the actual measurements are found in figure 16. In the upper plot the betatron dipole mode's amplitude ramps up for the first 3 msec and then decays exponentially thereafter. The lower plot shows one of the head-tail modes being excited. After the drive turns off, the initial 7 dB drop represents the component of the signal, which represents the excitation of the dipole mode; the roughly exponential shape thereafter is the head-tail mode's decay. If the longitudinal drive to the RF cavity's phase were to be turned, then off the head-tail mode's signal would go away.

This type of measurement may be very useful for understanding the behavior of bunches within the train before their motion becomes unstable. However, even though much of the data acquisition is automated, there are a few steps, which must be accomplished by the personnel taking data. In particular the fine adjustment of the spectrum analyzer's frequency, centering it on the coherent mode's frequency, is necessary to produce the exponential damping curve. The manual adjustment of the frequency makes this type of measurement fairly time-consuming. Routinely, after data is taken for several bunches, the beam is topped off. Beam size measurements are typically taken immediately after topping off.

CONCLUSIONS

This paper has presented details for the beam dynamics measurements performed in the Cesr-TA project. Different techniques for measuring the tunes, the coherent mode amplitudes and damping rates have been described. Information about the strengths and weaknesses of these techniques provide useful ways to rate the different strategies employed for these measurements.

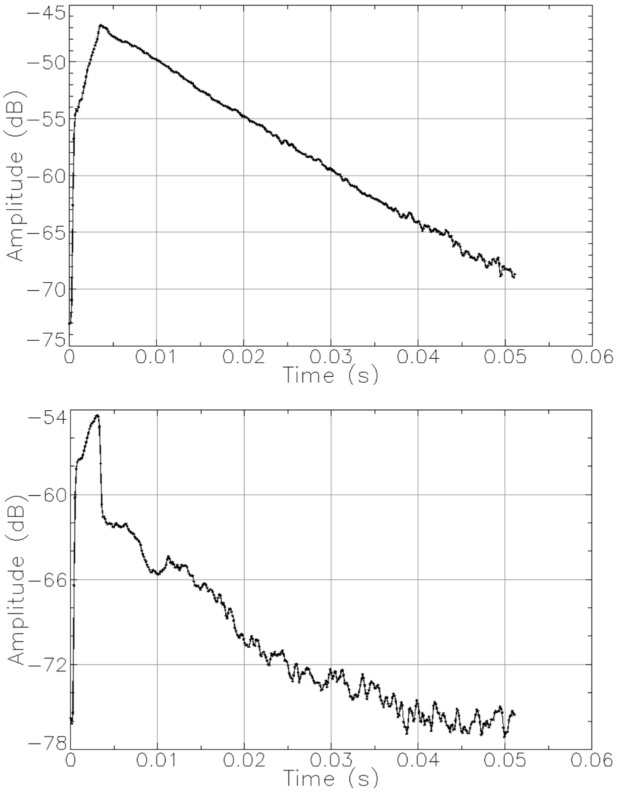


Figure 16: Drive-damp measurements: The upper trace is the response for the bunch being driven at the vertical betatron frequency. The lower trace is the response when one of the head-tail modes is excited. The vertical and horizontal scales are 5 dB and 10 msec per division, respectively.

REFERENCES

[1] M. Palmer, these proceedings.
[2] M. Palmer, "CESR Beam Position Monitor System Upgrade for CesrTA and CHESS Operations", Proceedings of 1st International Particle Accelerator Conference: IPAC'10, Kyoto, Japan, 23-28 May 2010
[3] N. Rider, these proceedings.
[4] Dimtel Inc., www.dimtel.com.
[5] CTA log entry 779.