STUDIES OF THE ELECTRON-CLOUD-INDUCED BEAM DYNAMICS AT CESR-TA*

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Abstract

At CesrTA, we have developed the capability to make automated measurements of the self-excited frequency spectra of individual bunches, to look for signals for single-bunch instabilities. We can also drive single bunches and measure the rate of decay of selected lines in their frequency spectra. We have used these capabilities to explore the dynamics of the interaction of a multi-bunch beam with the electron cloud. The basic observation is that, under conditions of sufficiently high current and sufficiently low chromaticity, the multi-bunch frequency spectra exhibit vertical $m = \pm 1$ synchrobetatron (head-tail) lines, separated from the vertical betatron line by the synchrotron frequency, for many of the bunches along the train. The amplitude of these lines typically (but not always) grows along the train. The dependence of this effect on many of the parameters of the beam has been explored.

OVERVIEW

Introduction

To continue our studies of electron cloud related phenomena, we have developed the capability to make automated measurements of frequency spectra of individual bunches, to look for signals for single-bunch instabilities.

In this measurement, a button BPM at 33W (sensitive to both vertical and horizontal motion) is gated on a single bunch, and the signal is routed to a spectrum analyzer. Several frequency spectra are acquired, covering a range which spans the lowest betatron sidebands. Machine conditions, such as bunch current, magnet settings, feedback system parameters, etc. are automatically recorded and stored before and after each single-bunch spectrum is taken.

Using this system, during the recent July-August, 2010, and September runs, a number of observations were made which illuminate the dynamics of the electron-cloud/beam interaction at CesrTA. This paper will review results from these experiments.

General remarks

All experiments discussed here were done at 2.085 GeV in a low emittance lattice. The machine parameters are shown in Table 1.

Table 1: Nominal machine parameters. The emittances and tunes are those of a single bunch in the machine.

Parameter	**Unit**	**Value**
Energy	GeV	2.085
Lattice		2085mev_20090516
Horizontal emittance	nm	2.6
Vertical emittance	pm	~ 20
Bunch length	mm	10.8
Horizontal tune		14.55
Vertical tune		9.58
Synchrotron tune		0.065
Momentum compaction		6.8×10^{-3}
Revolution frequency	kHz	390.13

Trains having bunches numbering from 30-45, with a bunch spacing of 14 ns, and bunch currents in the range of $0.5 - 1.25$ mA ($0.8 - 2.0 \times 10^{10}$ particles) per bunch were studied. In all cases, except where specifically noted, the beam particles were positrons.

Several systematic checks were undertaken:

- Checks were made to rule out intermodulation distortion in the BPM electronics and in the BPM itself.
- The betatron and synchrobetatron (head-tail) lines moved as expected when the vertical, horizontal, and synchrotron tunes were varied.

The longitudinal feedback was off for these measurements. The vertical and horizontal feedback were turned down to 20% of full power. Some experiments explored the effect of turning the vertical feedback fully off.

More details on the experimental technique can be found in [2].

General observations

The basic observation is that, under a variety of conditions, the frequency spectra exhibit the vertical $m = \pm 1$ synchrobetatron (head-tail) lines, separated from the vertical betatron line by the synchrotron frequency, for many of the bunches along the train. The amplitude of these lines typically (but not always) grows along the train.

Typically, for the bunch at which the vertical synchrobetatron lines first appear above the noise floor (which is about 40 db below the vertical betatron line), we observe (on a bunch-by-bunch X-ray beam size monitor) growth in the beam size, which continues to increase along the train [3].

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Under some conditions, the first bunch in the train also exhibits a synchrobetatron line ($m = -1$ only). The presence of a "precursor" bunch, placed about 180 ns before the train, eliminates the $m = -1$ signal in the first bunch.

Subsequent sections will present the details of these observations, together with their dependence on machine and beam parameters such as bunch current, number of bunches, chromaticity, synchrotron tune, beam emittance, vertical feedback, and particle species. In the final section, some preliminary observations on measurements of bunch-by-bunch damping rates are presented.

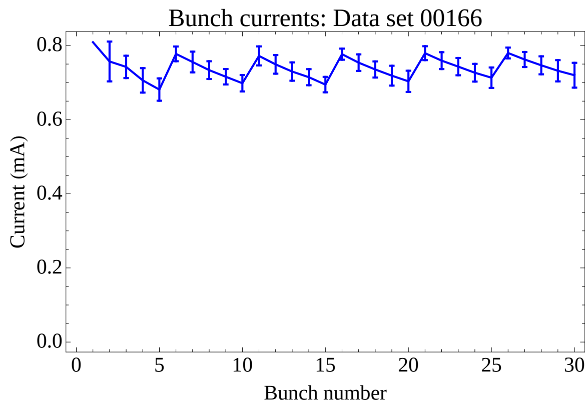

Figure 1: Data set 166: Bunch-by-bunch currents. See text for an explanation of the error bars.

BUNCH-BY-BUNCH POWER SPECTRUM

To measure a bunch-by-bunch power spectrum, the machine is loaded with a bunch train with a uniform current per bunch, and software is run to automatically collect frequency spectra from a button BPM gated on the first bunch. The data acquisition takes a few minutes, and the gate is then moved to the second bunch, and so on through the train. The gate width is much smaller than the bunch spacing, so only the motion of the gated bunch is observed. The frequency spectra are 10 s averages, acquired in 4 measurements, each with a 40 kHz span, covering the range from 170 to 330 kHz.

Since the beam has a relatively short lifetime, it is necessary to periodically pause the measurements and "top off" the bunch train. Typically, this is done after data acquisition is completed for a group of 5 bunches. Fig. 1 shows the beam current as a function of bunch number during a specific data set. In this figure, the current per bunch plotted for bunch n corresponds to the average value of the bunch current for all bunches earlier than bunch n; the error bar represents the rms variation in this number, principally due to irregularities in the fill. The dips at bunches 5, 10, . . ., and peaks at 6, 11, . . ., correspond to when the train is "topped off."

The bunch-by-bunch power spectrum observed in data set 166 is shown in Fig. 2. The figure plots the power spectrum for each bunch, as measured at the button BPM, vs. frequency. The four prominent peaks seen correspond, from lower to higher frequency, to the $m = -1$ vertical synchrobetatron line, the horizontal betatron line, the vertical betatron line, and the $m = +1$ vertical synchrobetatron line. Fig. 3 shows the spectrum of the last bunch, bunch 30, in greater detail. For this data set, the vertical chromaticity[1] was 1.16, and the horizontal chromaticity was 1.33.

The principal features exhibited in Fig. 2 and Fig. 3 are discussed in more detail in the next subsections.

POWER SPECTRUM FEATURES NEAR THE BETATRON LINES

Horizontal betatron lineshape

Fig. 4 shows the bunch-by-bunch power spectrum near the horizontal betatron line. There is a major peak which shifts up in frequency by about 4 kHz during the bunch train. This shift is attributable to the electron cloud. A quantitative comparison with simulations is presented below. In addition, there is a lower amplitude "shoulder", which appears to be roughly constant in frequency during the bunch train (i.e., there is no tune shift). A plausible explanation for this shoulder is the following: tune shift measurements and simulations[4] have shown that, when the all the bunches in the train are oscillating in-phase, the horizontal tune shift due to the electron cloud in a dipole-dominated ring such as CesrTA is very small. However, for the data set shown in Fig. 4, the bunches in the train are spontaneously excited, so a mixture of multibunch modes will be present. This mixture of multibunch modes will exhibit a spectrum of electron-cloud-induced tune shifts, ranging from nearly zero tune shift for the mode in which the bunches are oscillating in phase, to large tune shifts for modes in which bunches are oscillating with different phases. Qualitatively, this should produce a spectrum similar to that shown in Fig. 4.

Vertical betatron lineshape

Fig. 5 shows the bunch-by-bunch power spectrum near the vertical betatron line. In this case, there is a shift up in frequency of the major peak by about 2 kHz during the bunch train, which is again attributable to the electron cloud. In addition, there is a smaller peak at a higher frequency, present even on the first bunch, which appears to grow in amplitude and merge with the main peak near the end of the bunch train. Since this peak is present even for the first bunch, it is unlikely that it is due to a multibunch mode dependence of the vertical electron cloud tune shifts. Also, measurements and simulations[4] have shown that the dependence of the *vertical* tune shifts on the multibunch mode is much smaller than for the horizontal tune

[1] The chromaticity is defined as

$$\chi = \frac{dQ}{d\delta},$$

where δ is the relative momentum shift and Q is the tune.

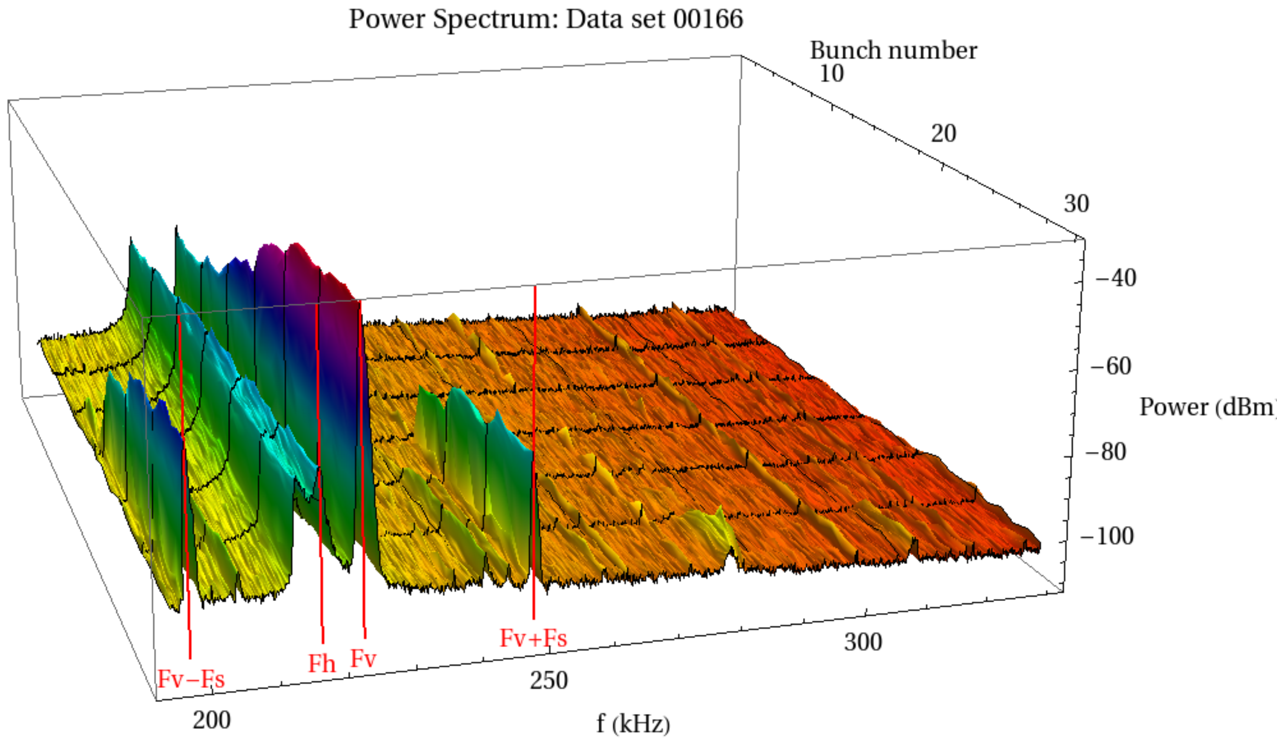

Figure 2: Data set 166: Bunch-by-bunch power spectrum.

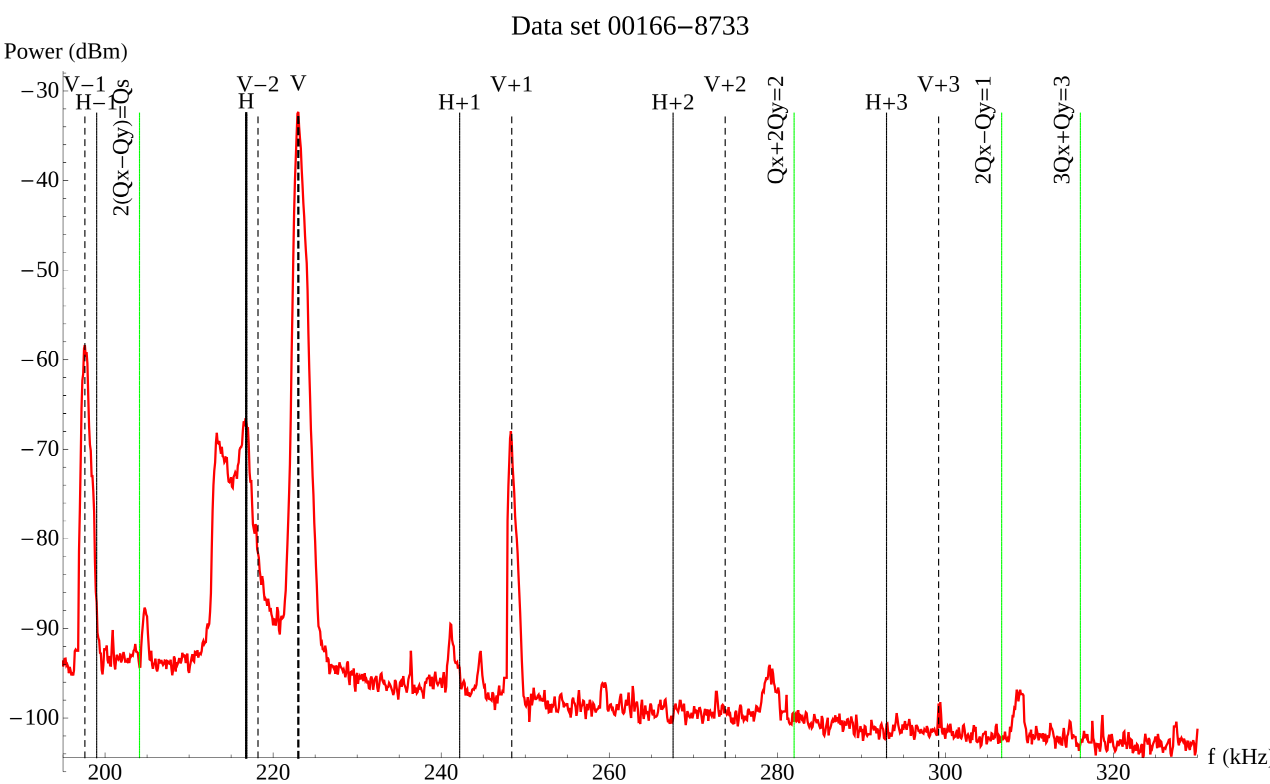

Figure 3: Data set 166: Power spectrum for bunch 30. The lines labelled, for example,“V+1” and “V-1” are shown at frequencies of $\pm f_s$ from the vertical betatron line (“V”), in which f_s is the synchrotron frequency. The locations of several machine resonances are also indicated.

shifts. This suggests that the structure in the vertical plane may be a single-bunch effect, but we have no good explanation for it.

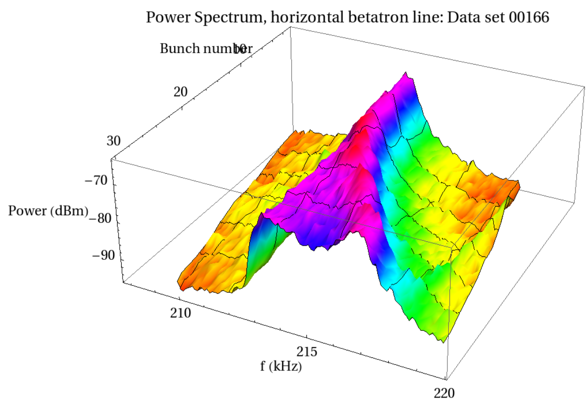

Figure 4: Data set 166: Bunch-by-bunch power spectrum: detail at horizontal betatron line. Chromaticity: (H,V) = (1.33, 1.16). Bunch current = 0.74 mA.

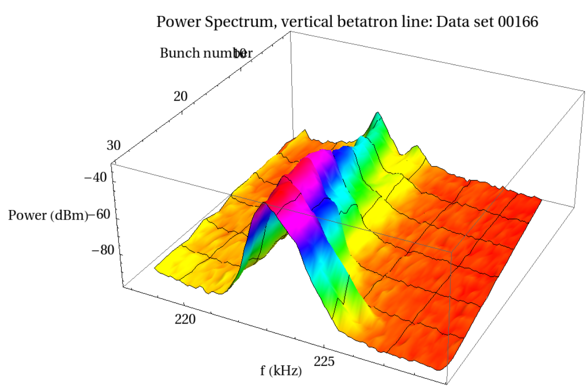

Figure 5: Data set 166: Bunch-by-bunch power spectrum: detail at vertical betatron line. Chromaticity: (H,V) = (1.33, 1.16). Bunch current = 0.74 mA.

Horizontal and vertical betatron lines: peak power and frequency

In Fig. 6, the peak power point[2] for each of the horizontal and vertical betatron lines is shown, as a function of bunch number. The strong excitation of vertical dipole motion is evident in the increase in vertical betatron line power along the train. There is minimal if any additional excitation in the horizontal plane.

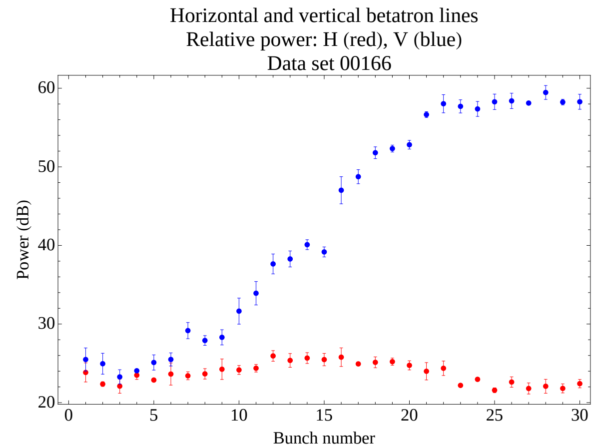

Figure 6: Horizontal and vertical peak power vs. bunch number, data set 166. Chromaticity: (H,V) = (1.33, 1.16). Bunch current = 0.74 mA.

In Fig. 7, the frequency of the peak power point is given, relative to the frequency of the first bunch. Thus, Fig. 7 illustrates the tune shift[3] along the train, which is primarily due to the electron cloud effect.

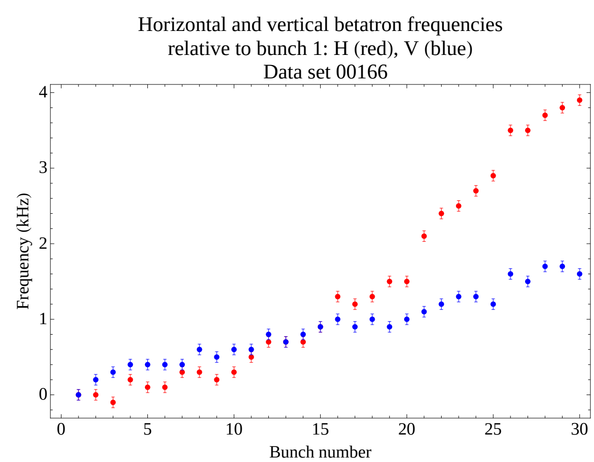

Figure 7: Horizontal and vertical tune shifts vs. bunch number, data set 166. Chromaticity: (H,V) = (1.33, 1.16). Bunch current = 0.74 mA.

Comparison with electron cloud buildup simulations

The cloud buildup program `POSINST` [1] can be used to compute the cloud density corresponding to a set of beam and vacuum chamber properties at CesrTA, and from this density the tune shifts can be computed. For this data, in

[2]For all the relative power plots shown in this paper, the plotted points were obtained as follows: A frequency region is selected, 10 kHz wide, centered approximately on the frequency of interest. The average background power level in this region is determined. Then, the maximum value of the power in this region is found, and subtracted from the background power level, to obtain the relative power.

Because of this background subtraction, if the relative power is close to zero (as in the plots of head-tail line power later in the paper), this signifies the absence of any significant peak.

The frequency plots correspond to the frequencies of the peak power points.

The errors shown in the frequency plots correspond to the bin widths of the frequency spectra (100 Hz). The errors shown in the relative power plots are estimated from the variation in the power over a spectral bin width.

[3]The tune shift is given in frequency units.

which the betatron lines are self-excited, it is reasonable to suppose that the dominate mode of oscillation of the bunches in the train is one in which each bunch is oscillating with a different phase than other bunches in the train. Under this condition, a good estimate of the tune shift can be calculated from the field gradient of the electron cloud's electric field, averaged over the transverse distribution of the bunch, and evaluated before the beam "pinches" the cloud [5].

These calculations (see [4] for details of the assumptions and methodology) can be compared with the measured tune shifts shown in Fig. 7. Comparisons between simulations and measurements are shown in Fig. 8 and Fig. 9. The key parameters used in the POSINST simulation are given in Table 2.

The error bars on the simulated points are due to macroparticle statistics; for the vertical tune shifts, the comparison would benefit from an increased number of macroparticles, which was not feasible due to computer run time limitations. Nevertheless, inspection of Fig. 8 and Fig. 9 indicates that the simulation compares well with the data.

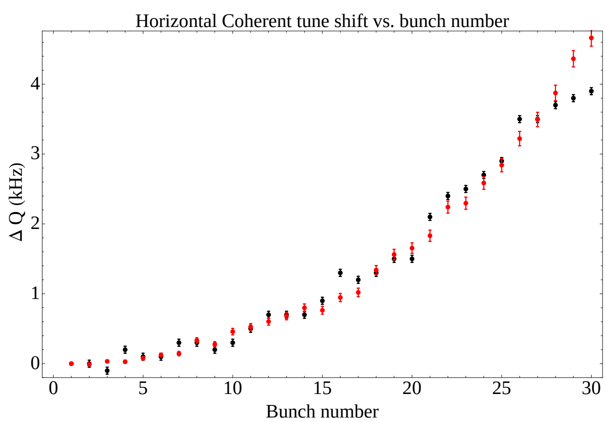

Figure 8: Data set 166: Horizontal tune shift vs. bunch number, comparison between data (black) and simulation (red) from POSINST with parameters given in Table 2.

ESTIMATES OF THE ELECTRON CLOUD DENSITY

Cloud density from measured betatron tune shifts

In this section, the measured tune shift is used to estimate the average electron cloud density. For a lattice in which the beta functions are equal in both planes, the electron-cloud-induced tune shifts δQ_x and δQ_y may be directly related to the average electron cloud density $\langle \rho_c \rangle$ via the relation

$$\langle \rho_c \rangle = \gamma \frac{\delta Q_x + \delta Q_y}{r_e \langle \beta \rangle C},$$

in which $\langle \beta \rangle$ is the average beta function, C is the ring circumference, γ is the beam Lorentz factor, and r_e is the classical electron radius. This relation may be used to obtain an estimate of the cloud density along the train. For CesrTA, we use $C = 649$ m (sum of all drift and dipole lengths) and $\langle \beta \rangle = 16$ m. The cloud densities for each bunch resulting from this calculation are shown as the red points in Fig. 10.

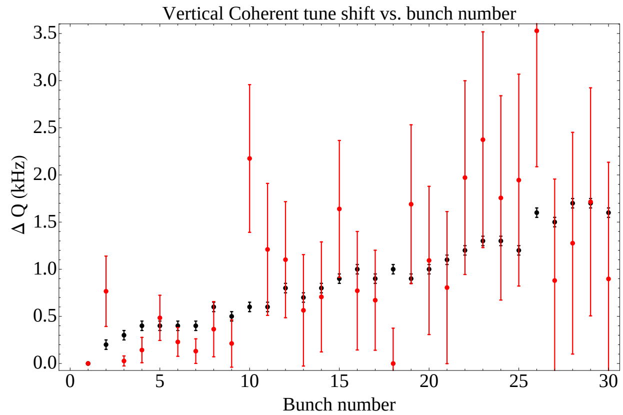

Figure 9: Data set 166: Vertical tune shift vs. bunch number, comparison between data (black) and simulation (red) from POSINST with parameters given in Table 2.

Comparison with electron cloud buildup simulations

We can compare the cloud density, obtained from the measured tune shifts, with the density obtained from the POSINST simulations discussed in the previous section. This comparison is shown in Fig. 10. For the simulation result, shown as black dots in the figure, the cloud density is evaluated at the time corresponding to the leading edge of the bunch (i.e., before the "pinch"), and is averaged over the transverse profile of the beam. The density shown is the weighted average over drifts (total length 175 m) and dipoles (total length 474 m). It is clear from Fig. 10 that the cloud density computed directly from the tune shifts is quite close to the simulation result.

VERTICAL HEAD-TAIL LINES

Head-tail line power and frequency characteristics

As shown in Fig. 2 and Fig. 3, there are two lines which appear in the bunch-by-bunch power spectrum, starting part way along the train, which have frequencies which are close to the betatron frequency plus and minus the synchrotron frequency. In Fig. 11 and Fig. 12, we plot the power and frequency (relative to the vertical betatron line, $\pm$ the synchrotron frequency) of these lines . We associate the lower frequency line with the $m = -1$ head-tail line, which arises as a result of head-tail bunch motion driven by the broadband impedance of the electron cloud. Similarly, we associate the higher frequency line with the $m = +1$

Table 2: POSINST simulation parameters (aluminum chamber, 2 GeV CesrTA positron beam)

POSINST **Parameter**	**Description**	**Unit**	**Value**
photopbppm (drift)	Photons/beam particle/meter (in a drift)	m^{-1}	0.272
photopbppm (dipole)	Photons/beam particle/meter (in a dipole)	m^{-1}	0.522
queffp	Quantum efficiency	%	12
refleff	Reflectivity	%	15
ek0phel	Peak photoelectron energy	eV	5
eksigphel	RMS photoelectron energy	eV	5
E0tspk	Energy of peak secondary yield	eV	310
dtotpk	Peak secondary yield		2.05
P1epk	Elastic yield at zero energy		0.5
P1rinf	Rediffused yield at high energy		0.19

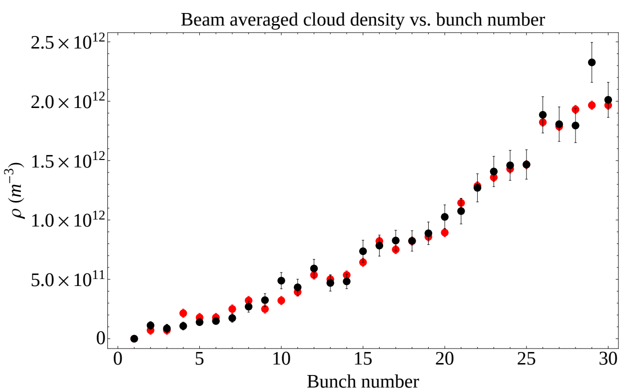

Figure 10: Data set 166: Average initial (i.e., before the "pinch") electron cloud density vs. bunch number, comparison between estimate from measured tune shifts (red), and simulation (black) from POSINST with parameters given in Table 2.

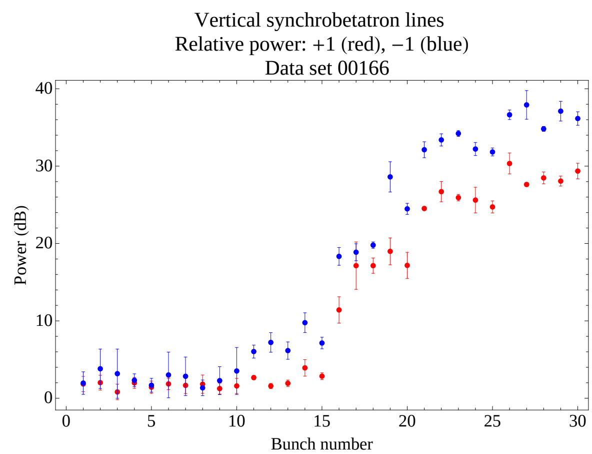

Figure 11: Data set 166: Vertical head tail lines: peak power vs. bunch number. Chromaticity: (H,V) = (1.33, 1.16). Bunch current = 0.74 mA.

head-tail line. From Fig. 11, we see that these lines appear above the noise level around bunch 15 or 16. The $m = -1$ line is somewhat more strongly excited than the $m = +1$ line.

Observations of beam size growth under similar beam conditions [3] see rapid emittance growth starting at about the same point in the train.

Fig. 12 shows that, for bunch numbers greater than about 15, where the head-tail lines appear above the background, the frequency of these head-tail lines, relative to the vertical line, is equal to the synchrotron frequency (within the errors).

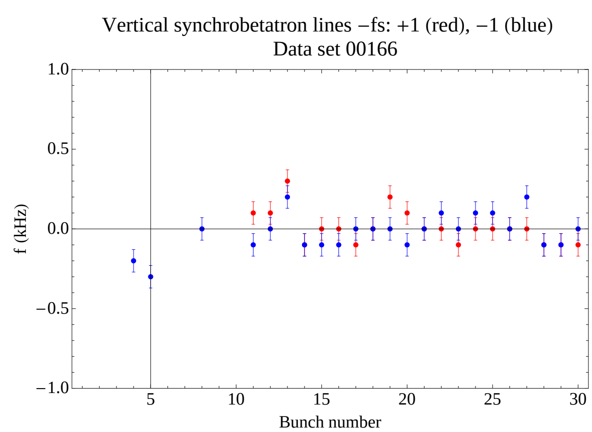

Figure 12: Data set 166: Vertical head tail lines: frequency difference from vertical betatron line vs. bunch number, with the synchrotron frequency removed from the offset.

Head-tail lines: correlation with cloud density

Comparing Fig. 10 and Fig. 11, the average electron cloud density at which the head-tail lines are first observed can be established. For the conditions of data set 166, the head-tail lines emerge at an initial (i.e., before the "pinch") beam-averaged cloud density around 8×10^{11} m^{-3}.

REPRODUCIBILITY

The reproducibility of the observations of the head-tail lines is illustrated in Fig. 13 and Fig. 14. These plots show the power in the vertical head-tail lines for two data sets taken on different dates (data set 147 on 9/25/2010, and data set 157 on 9/26/2010) but under the same nominal machine and beam conditions as data set 166. Comparing Fig. 13 and Fig. 14 with each other and with Fig. 11 indicates good consistency between the observations of the head-tail lines.

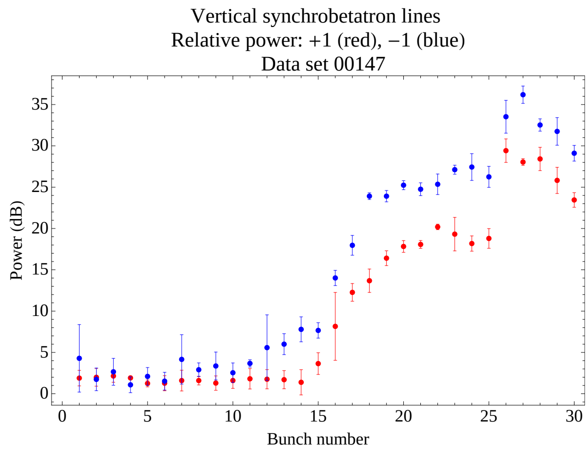

Figure 13: Data set 147: Vertical head tail lines: peak power vs. bunch number. Chromaticity: (H,V) = (1.33, 1.16). Bunch current = 0.74 mA.

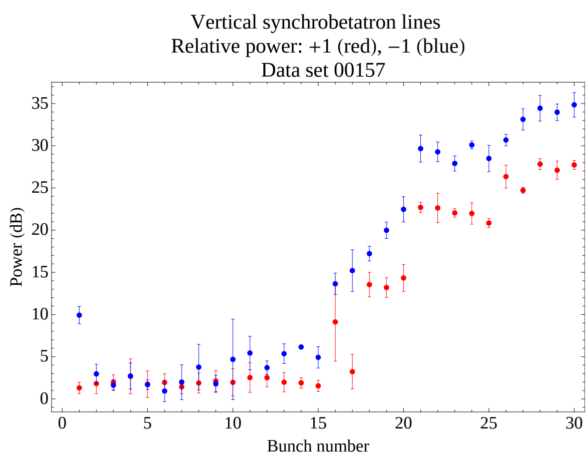

Figure 14: Data set 157: Vertical head tail lines: peak power vs. bunch number. Chromaticity: (H,V) = (1.33, 1.16). Bunch current = 0.73 mA.

CHROMATICITY DEPENDENCE

The chromaticity dependence of the head-tail lines is illustrated by comparing Fig. 13, Fig. 15 and Fig. 16. For all data sets, the nominal bunch current was abut 0.74 mA. We see that for data set 142 (Fig. 15), with a higher value of the vertical chromaticity than data set 147, there are no head-tail lines observed. For data set 129 (Fig. 16), with lower values of both chromaticities than data set 142, but a higher value of the vertical chromaticity than data set 147, head-tail lines are observed, but their onset is a few bunches later in the train than in data set 147, which has the lowest vertical chromaticity.

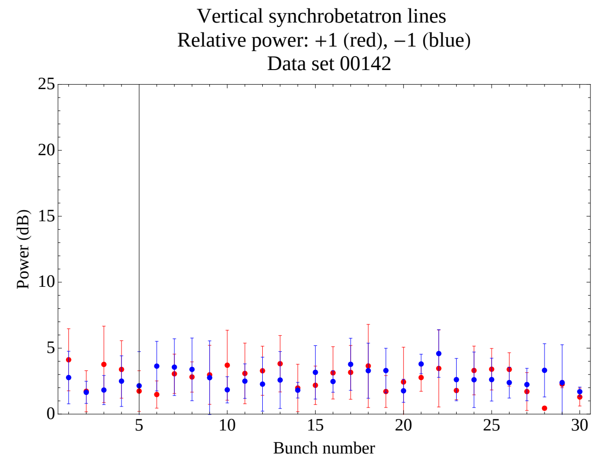

Figure 15: Data set 142: Vertical head tail lines: peak power vs. bunch number. Chromaticity: (H,V) = (1.34, 1.99). Bunch current = 0.74 mA.

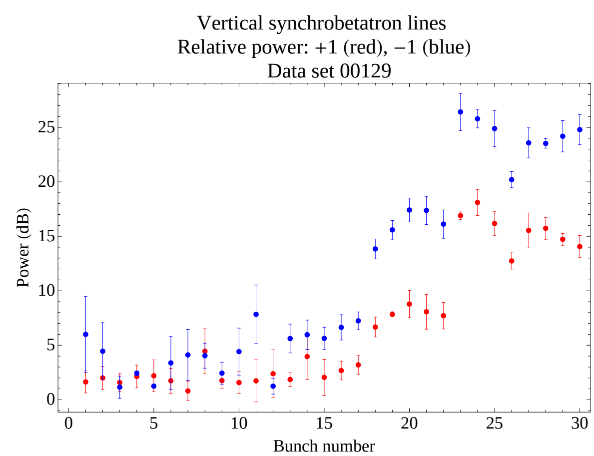

Figure 16: Data set 129: Vertical head tail lines: peak power vs. bunch number. Chromaticity: (H,V) = (1.07, 1.78). Bunch current = 0.74 mA.

CURRENT DEPENDENCE

The current dependence of the head-tail lines is illustrated by comparing Fig. 15 and Fig. 17. Both data sets have the same chromaticity, but the data set with the lower bunch current (data set 142) shows no head-tail lines, while the higher current data set (data set 150) shows head-tail lines staring to emerge around bunch 12. Similarly, we can compare Fig. 13 and Fig. 18. Again, both data sets have the same (lower) chromaticity, but the data set with the lower bunch current (data set 178) shows no head-tail lines, while the higher current data set (data set 147) shows head-tail lines staring to emerge around bunch 16.

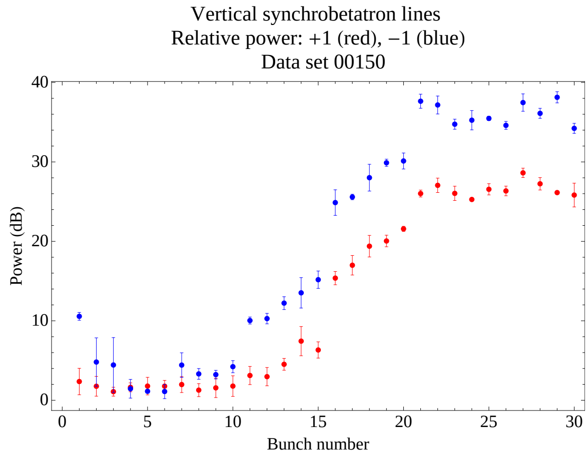

Figure 17: Data set 150: Vertical head tail lines: peak power vs. bunch number. Chromaticity: (H,V) = (1.34, 1.99). Bunch current = 0.95 mA.

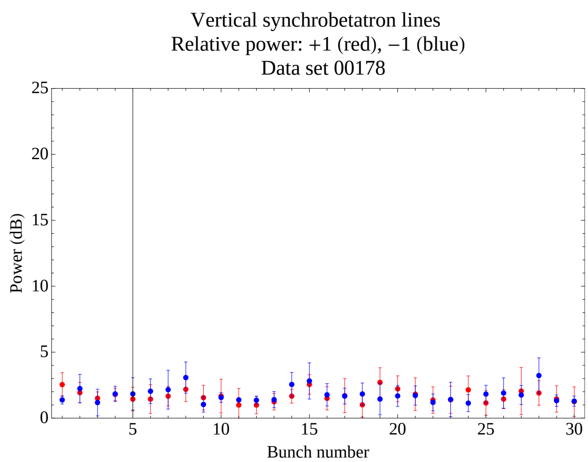

Figure 18: Data set 178: Vertical head tail lines: peak power vs. bunch number. Chromaticity: (H,V) = (1.34, 1.11). Bunch current = 0.5 mA.

BUNCH NUMBER DEPENDENCE

The bunch number dependence of the head-tail lines is illustrated by comparing Fig. 15 with Fig. 19. Both data sets have the same chromaticity and bunch current, but data set 156 contains 45 bunches in the train. The vertical tunes of the first bunch were slightly different for the two runs: for run 142, it was about 227 kHz, while for run 156 the tune was about 221 kHz. No head-tail lines are observed in data set 142 (Fig. 15) out to the end of the train, bunch 30. But with 45 bunches, head-tail lines are observed starting around bunch 18, then growing to a peak around bunch 25, and falling off at the end of the train. The fact that the head-tail lines are seen with a 45 bunch train with the same bunch current as a 30 bunch train for which no lines are seen, is suggestive that there is a residual cloud density which lasts more than one turn, and which depends on the total current.

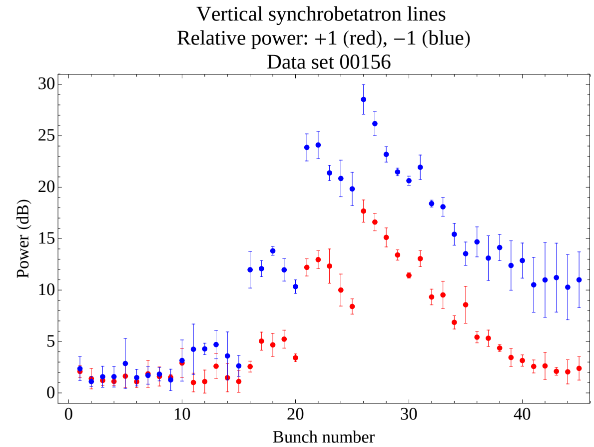

Figure 19: Data set 156: Vertical head tail lines: peak power vs. bunch number. Chromaticity: (H,V) = (1.34, 1.99). Bunch current = 0.73 mA. The increased amplitude at bunches 21 and 26 is an artifact due to refilling of the train at these bunch numbers.

45 bunch train: Correlation with cloud density

In Fig. 20, we show the cloud density as a function of bunch number, computed from the measured tune shifts, as discussed above. Comparison with Fig. 19 shows that the head-tail lines emerge from the background at a cloud density of about 8×10^{11} m^{-3}, which is the same as the threshold density found for data set 166, even though the vertical chromaticity was higher for data set 156. The fall-off of the head-tail lines after bunch 25 suggests that the instability is saturating. Yet the cloud density continues to increase after bunch 25 (at least until around bunch 35) as Fig. 20 shows. The head-tail instability threshold is expected to be sensitive to the beam size, so what may be happening is that the instability is driving beam size growth along the train, and the increase in the threshold as the beam size increases provides a mechanism for the instability to saturate.

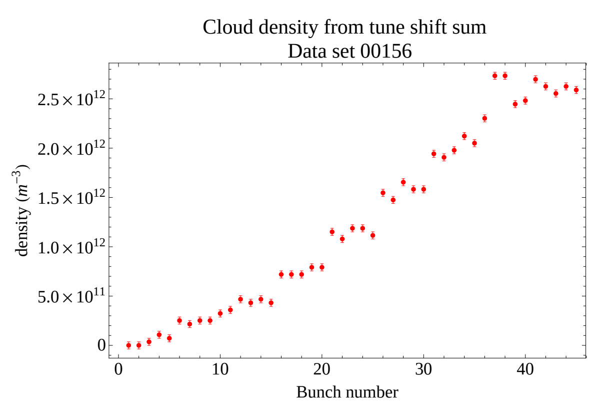

Figure 20: Average initial electron cloud density vs. bunch number, estimate from measured tune shifts, data set 156

SYNCHROTRON TUNE DEPENDENCE

The synchrotron tune dependence of the head-tail lines is illustrated by comparing Fig. 13 and Fig. 21. Both data sets have the same chromaticity and bunch current, but data set 151 (Fig. 21) has a reduced synchrotron frequency of 20.7 kHz, and an increased bunch length of 12.8 mm. The nominal frequency and bunch length, for data set 147 (Fig. 13) are 25.4 kHz and 10.8 mm.

For both data sets, the separation between the vertical betatron lines and the head-tail lines equals the synchrotron frequency. A comparison of Fig. 13 and Fig. 21 shows that the head-tail line threshold is about the same in both cases, but the power in the lines grows more slowly with bunch number for the data set with a reduced synchrotron tune.

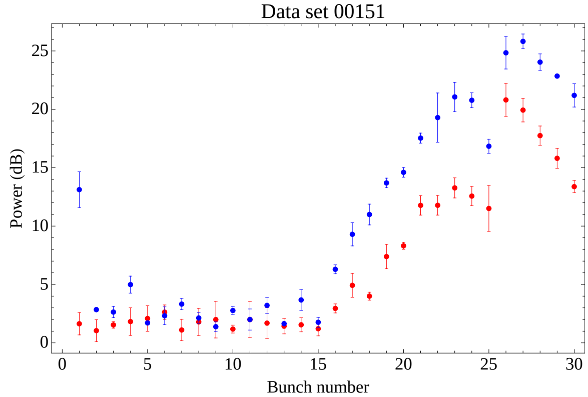

Figure 21: Data set 151: Vertical head tail lines: peak power vs. bunch number. Chromaticity: (H,V) = (1.33, 1.16). Bunch current = 0.74 mA. Synchrotron frequency 20.7 kHz, bunch length 12.8 mm

SINGLE-BUNCH VERTICAL EMITTANCE DEPENDENCE

The vertical emittance dependence of the head-tail lines is illustrated by comparing Fig. 13 and Fig. 22. Both data sets have the same chromaticity and bunch current, but data set 158 (Fig. 22) has an increased single-bunch vertical emittance of 300 pm[4]. The nominal single-bunch vertical emittance, for data set 147 (Fig. 13), is $\sim$ 20 pm.

A comparison of Fig. 13 and Fig. 22 shows that the head-tail line threshold is a few bunches earlier for the data set with increased vertical emittance, but the power in the lines grows more slowly with bunch number for data set 158. Generally, there is not a great deal of difference, which is peculiar, since the electron cloud head-tail instability is expected to considerably more severe for smaller vertical emittance. It is possible that, due to emittance growth along the train, the vertical emittance of the bunch at which the instability starts is larger than the single-bunch vertical emittance.

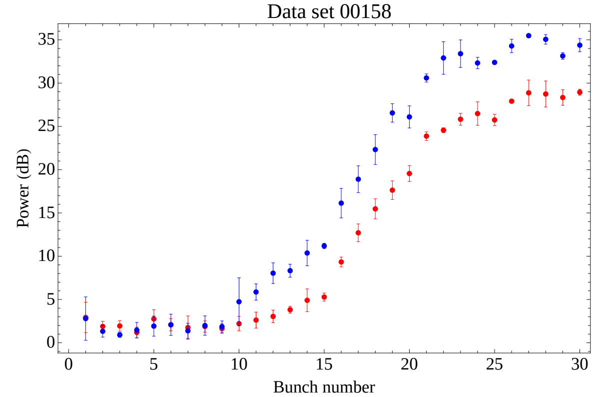

Figure 22: Data set 158: Vertical head tail lines: peak power vs. bunch number. Chromaticity: (H,V) = (1.33, 1.16). Bunch current = 0.77 mA. Single-bunch vertical emittance $\sim$ 300 pm (estimated).

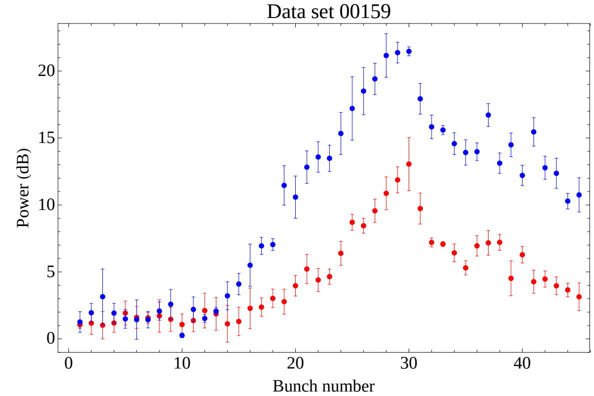

Figure 23: Data set 159: Vertical head tail lines: peak power vs. bunch number. Chromaticity: (H,V) = (1.34, 1.99). Bunch current = 0.75 mA. Single-bunch vertical $\sim$ 300 pm (estimated).

Another observation which explores the vertical emittance dependence of the head-tail lines is illustrated by comparing Fig. 19 and Fig. 23. Both data sets have 45 bunches and have the same chromaticity and bunch current, but data set 159 (Fig. 23) has an increased single-bunch vertical emittance of $\sim$ 300 pm. The single-bunch vertical emittance, for data set 156 (Fig. 19), is $\sim$ 20 pm.

Again, a comparison of Fig. 19 and Fig. 23 shows that the head-tail line threshold is a few bunches earlier for the data set with increased vertical emittance, but the power in the lines grows more slowly with bunch number for data set 159. In this case, the power peaks later in the train, and at a smaller value, for the data set with increased emittance. The saturation effect is observed for both values of

[4]This number was estimated from a lattice model, not directly measured.

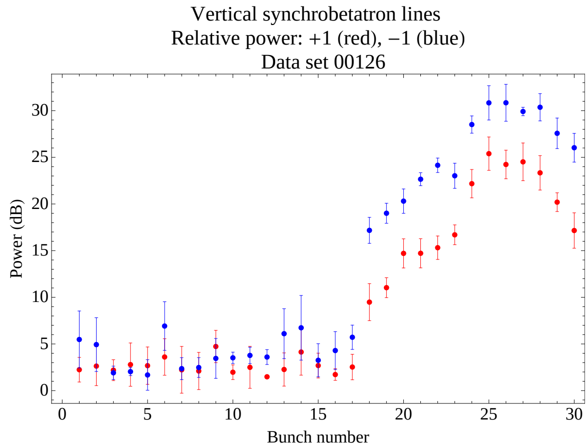

Figure 24: Data set 126: Vertical head tail lines: peak power vs. bunch number. Chromaticity: (H,V) = (1.07, 1.78). Bunch current = 0.72 mA. Vertical feedback off.

the single-bunch vertical emittance.

VERTICAL FEEDBACK DEPENDENCE

The vertical feedback dependence of the head-tail lines is illustrated by comparing Fig. 16 and Fig. 24. Both data sets have the same chromaticity and bunch current, but data set 126 (Fig. 24) has the vertical (dipole) feedback off. For data set 129 (Fig. 16), as for all the other data sets discussed here (except 126), the vertical feedback is set to 20% of full gain.

A comparison of Fig. 16 and Fig. 24 shows that the head-tail line threshold is about in the same place for these two data sets. But for data set 129, the peak power rises to about 25 db by bunch 22, and then plateaus. For data set 126 (feedback off), it increases to about 32 db by bunch 25, and then starts to decay.

PARTICLE SPECIES DEPENDENCE

The species dependence of the bunch-by-bunch power spectrum is illustrated by comparing data set 166 (Fig. 2) and data set 154 (Fig. 25). Both data sets have the same chromaticity and bunch current, but data set 154 is for electrons. For electrons, we see less vertical excitation along the train, and smaller head-tail line excitation, than for positrons. The large tune shifts observed with the positron beam are also absent.

The details of the different structures of the head-tail lines for electrons and positrons can be seen by comparing Fig. 11 and Fig. 26. For electrons, the head-tail lines start later in the train, and at their maxima are 20 dB lower than the positron head-tail lines.

The positron head-tail excitation is presumably due to electron cloud effects. The physical mechanism responsible for the head-tail excitation in the electron case is not likely to be either electron cloud or positive ions. It may be due to the broad-band impedance of the machine itself.

PRECURSOR BUNCH EXPERIMENT

In Fig. 27, the power spectrum of bunch 1 for data set 151 is shown. Note the presence of a prominent $m = -1$ head-tail line. This line disappears for the second bunch, and does not re-appear until much later in the train, as shown in Fig. 21. Moreover, beam size measurements[3] indicate that the first bunch in the train is frequently larger in size than the next few bunches.

This suggests that the cloud density near the beam, which persists after the train ends, may be sufficiently high, even for the first bunch in the train, that spontaneous head-tail motion occurs. However, the interaction of the first bunch with this cloud evidently decreases the cloud density near the beam, so that bunch 2 does not suffer from spontaneous head-tail motion.

Simulations and witness bunch measurements indicate that the electron cloud lifetime in dipoles and drifts is much shorter than one turn in CesrTA. Cloud density which persists for many turns may be due to trapped cloud in quadrupoles and wigglers. Simulations and RFA measurements in quadrupoles have both indicated that trapped cloud may be present.

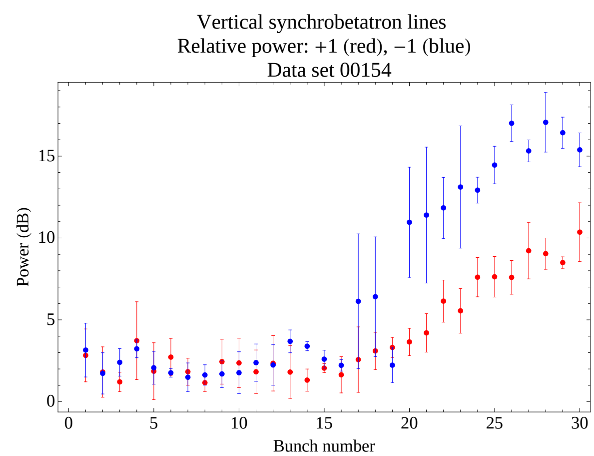

Figure 26: Data set 154: Vertical head tail lines: peak power vs. bunch number. Chromaticity: (H,V) = (1.33, 1.16). Bunch current = 0.76 mA. Electrons.

To test this hypothesis, in data set 153, a 0.75 mA “precursor” bunch was placed 182 ns before bunch 1. Otherwise, conditions were the same as for data set 151. The spectrum of the first bunch for data set 153 is shown in Fig. 28. Note that the head-tail line is now absent. In addition, the structure seen on the upper edge of the vertical betatron line in Fig. 27 is also absent. In Fig. 29, the power in the vertical head-tail lines is shown as a function of bunch number, for data set 153. Comparing with data set 151 (Fig. 21), it can be seen that the power in the lines near the end of the train is somewhat lower (perhaps 5 db) when the precursor bunch is present.

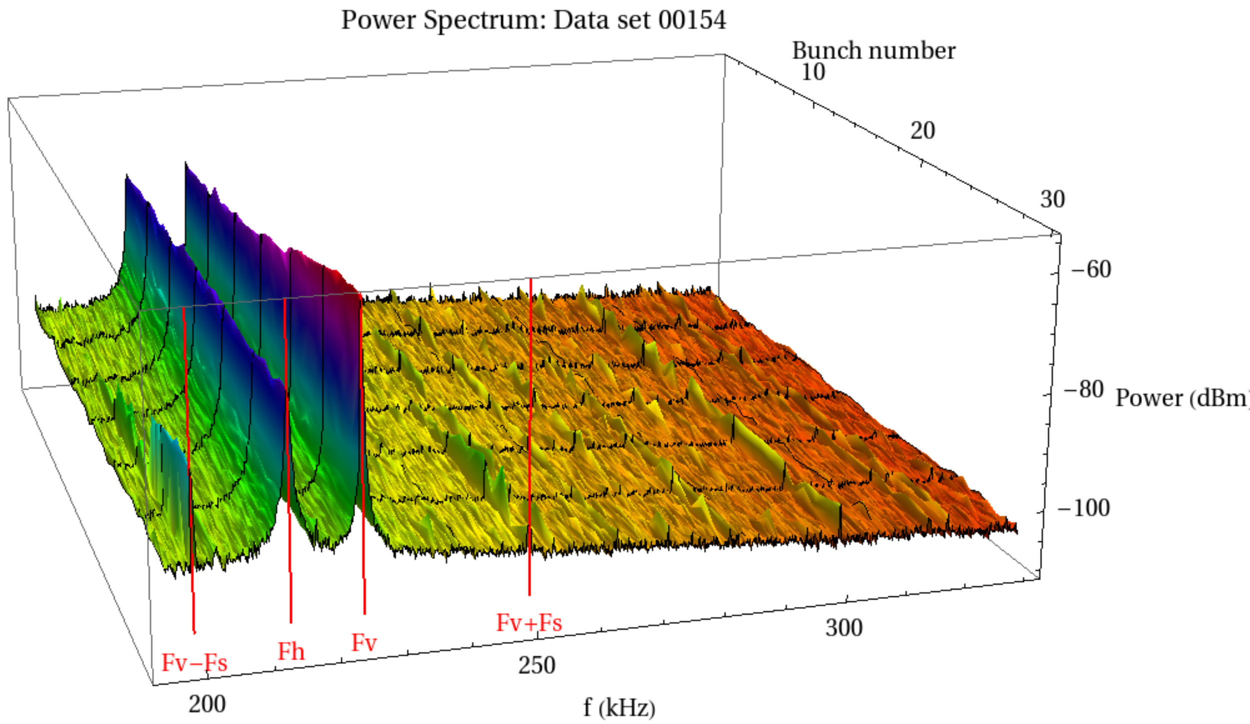

Figure 25: Data set 154: Bunch-by-bunch power spectrum. This data set is for electrons, but has the same chromaticity and bunch current parameters as data set 166 (Fig. 2).

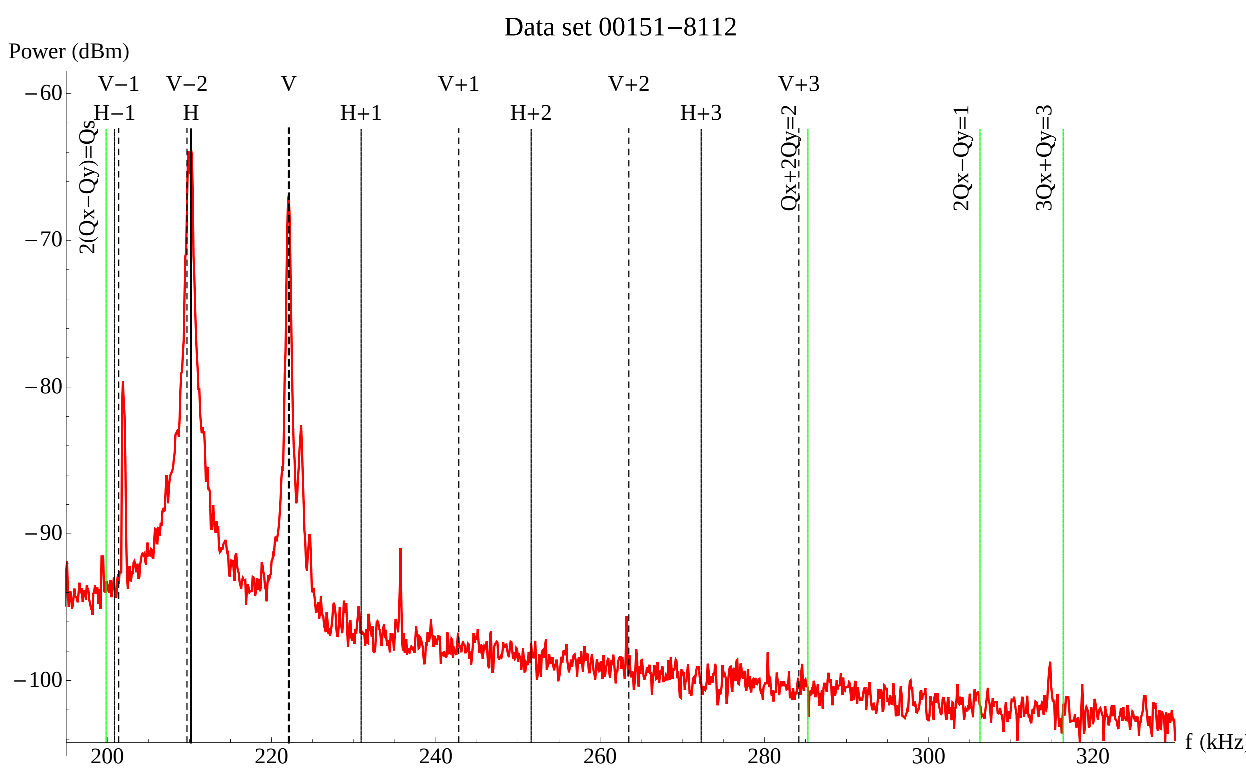

Figure 27: Data set 151: Power spectrum, bunch 1. The lines labelled, for example,"V+1" and "V-1" are shown at frequencies of $\pm f_s$ from the vertical betatron line ("V"), in which f_s kHz is the synchrotron frequency. The location of several machine resonances are also indicated.

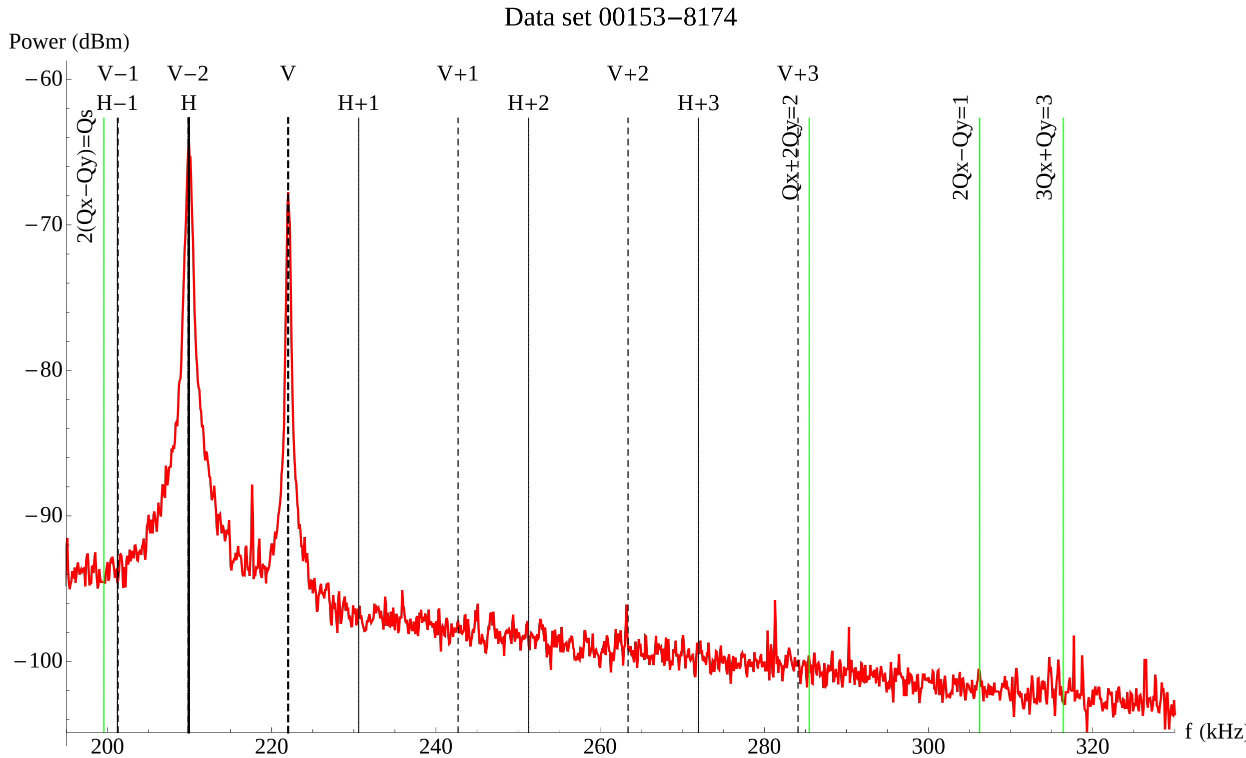

Figure 28: Data set 153: Power spectrum, bunch 1. This data set has the same conditions as data set 151, except for the presence of an additional 0.75 mA "precursor" bunch placed 182 ns before bunch 1.

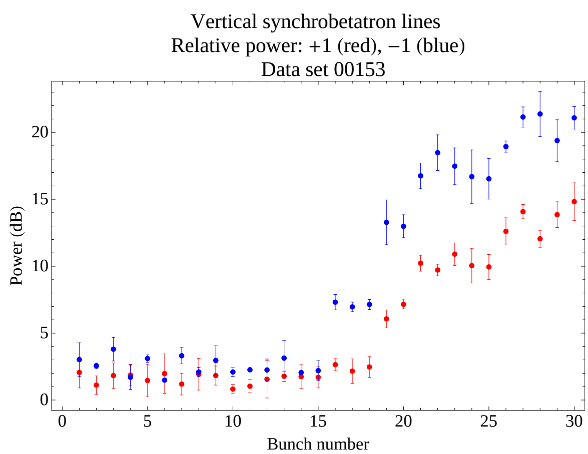

Figure 29: Data set 153: Vertical head tail lines: peak power vs. bunch number. Chromaticity: (H,V) = (1.33, 1.16). Bunch current = 0.74 mA. Precursor bunch present.

SINGLE BUNCH CURRENT VARIATION EXPERIMENT

To explore further the dynamics of the interaction of the last bunch in the train with the cloud, a series of power spectral measurements were made, in which the current in the first 29 bunches in a 30 bunch train was fixed, but the current in the last bunch was varied. The power spectrum with the last bunch at 0.25 mA is shown in Fig. 30, while the power spectrum with the last bunch at 1.25 mA is shown in Fig. 31.

The vertical excitation of the bunch, both at the vertical betatron line and at the head-tail lines, is much larger for the higher current bunch. The $m = +1$ head-tail line appears to acquire a low-frequency shoulder at the higher current.

In addition, while it is hard to see from these figures, the frequency of the vertical betatron line is almost independent of the current in the bunch. The shift from 0.25 mA to 1.25 mA is less than 0.2 kHz. Note that this behavior is very different from what would be expected for a conventional machine impedance, for which one would expect a strong current dependence for the tune.

BUNCH-BY-BUNCH DAMPING RATES: METHODOLOGY

In addition to the power spectrum measurements described above, in which spontaneous excitations of single bunches are passively monitored, we have also made measurements in which we actively excite a single bunch in a train, and measure the rate at which the bunch damps after the excitation is turned off. These bunch-by-bunch damping rate measurements come in two varieties:

- $m = 0$ *(dipole mode).* In this case, we drive a single bunch by delivering a narrow pulse to the transverse feedback system's kicker. We observe the $m = 0$

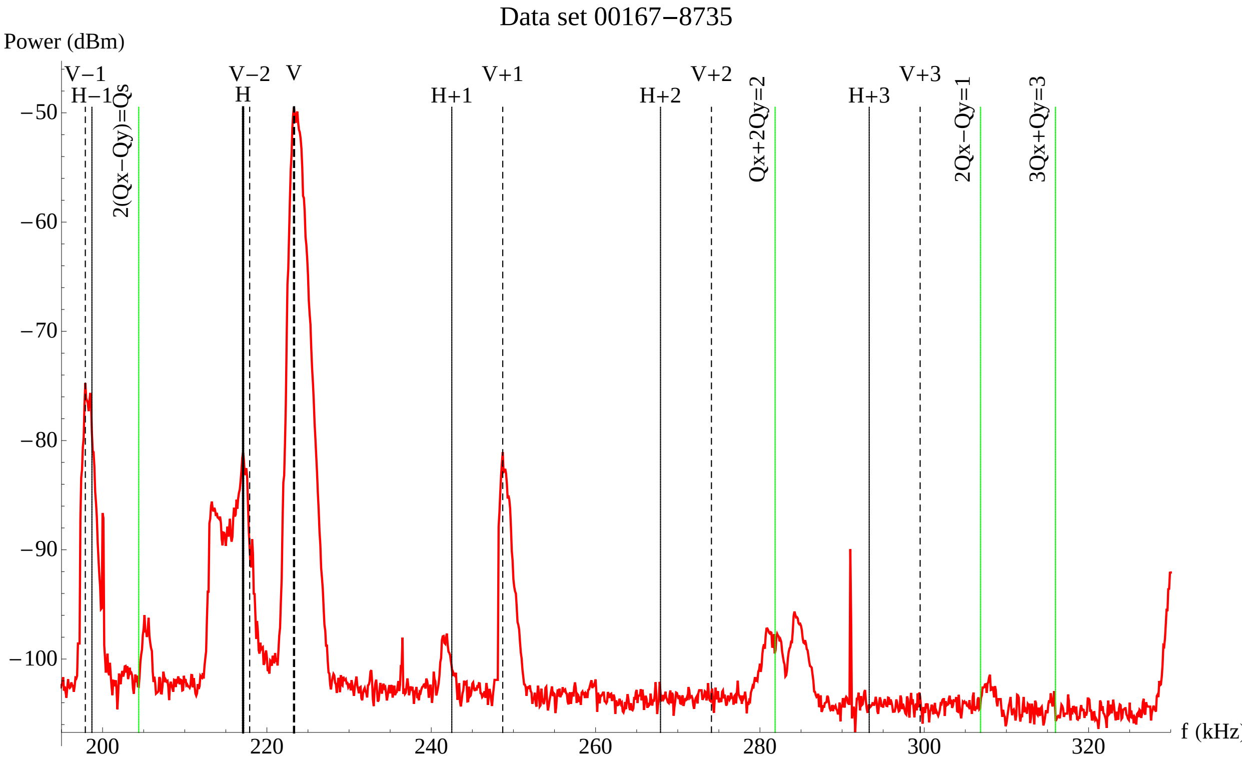

Figure 30: Data set 167: Power spectrum, bunch 30. Bunch 30 current = 0.25 mA. The first 29 bunches had a nominal current of 0.75 mA/bunch. Chromaticity: (H,V) = (1.33, 1.16).

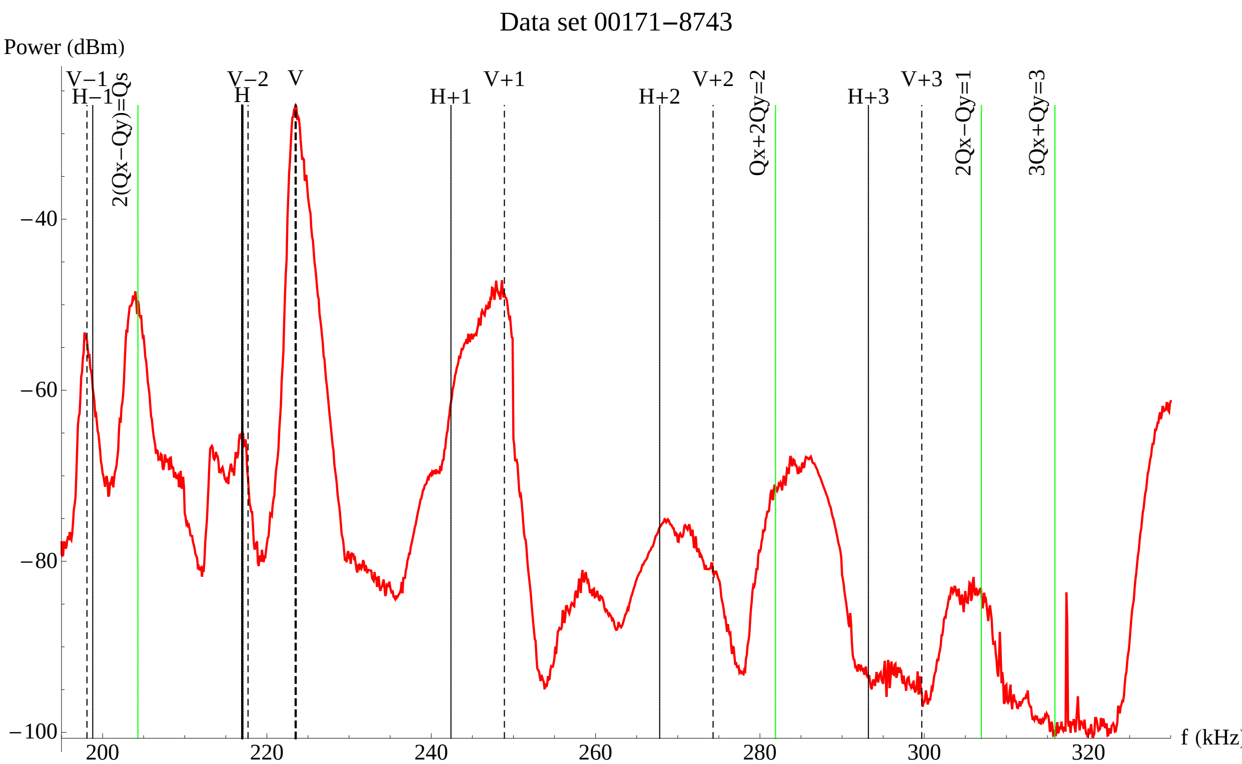

Figure 31: Data set 171: Power spectrum, bunch 30. Bunch 30 current = 1.25 mA. The first 29 bunches had a nominal current of 0.75 mA/bunch. Chromaticity: (H,V) = (1.33, 1.16).

motion (betatron line) on a button BPM, gated on the same bunch. Using a spectrum analyzer in zero span mode, tuned to the betatron line, we measure the damping rate of the $m = 0$ line's power after the drive is turned off.

- $m = \pm 1$ *(head tail modes).* In this case, we apply a CW drive to the RF cavity phase, to provide a large amplitude longitudinal excitation. We then perform a transverse drive-damp measurement, as in the previous case, but with the spectrum analyzer tuned to the head-tail line's frequency.

A number of measurements were made to investigate the systematics of this technique. More details can be found in [2].

Results will be shown here for two data sets in which 30 bunch trains with currents of about 0.75 mA/bunch were studied. (For these conditions, the self-excited head-tail lines first appear above background around bunch 15).

DRIVE-DAMP MEASUREMENTS

For the two data sets, we show the line power as a function of time, and bunch number. For data set 182 (Fig. 32), the $m = 0$ mode was excited and monitored. For data set 177 (Fig. 33), the $m = -1$ mode was excited and monitored.

In data set 182, the first bunch is more easily excited than the next few bunches, but the damping rates are similar. But further along the train, the excitation level increases and the damping time gets very long near the end of the train. This is consistent with reduced stability for the later bunches.

In data set 177, we see a similar trend, except that the first few bunches all appear to have similar damping times and excitation levels. Again, further along the train, the excitation level increases and the damping time gets very long near the end of the train.

Generally, the fastest damping rates observed in these data sets are on the order 200 s^{-1}, which is much larger than the radiation damping rate. The feedback system was set to 20% of maximum for these measurements. At this level, and for 0.75 mA/bunch, the feedback system provides a damping rate of a few hundred s^{-1}. Thus, the fastest rates observed are consistent with what is expected from the feedback system. Future measurements are planned in which the feedback system will be gated off for the bunch being excited and measured.

CONCLUSIONS

The basic observation is that, under a variety of conditions, single-bunch frequency spectra in multi-bunch positron trains exhibit the $m = \pm 1$ head-tail (HT) lines, separated from the vertical line by the synchrotron frequency, for some of the bunches during the train. A summary of more detailed observations follows in the following bullets.

- For a 30 bunch train with 0.75 mA/bunch, the onset of the HT lines occurs at a ringwide initial (i.e., before the "pinch") beam-averaged cloud density of around 8×10^{11} m^{-3} (assuming no cloud density at the start of the train).
- The betatron lines exhibit structure which varies along the train. The vertical line power grows along the train and has a fine structure that is not understood.
- The onset of the HT lines depends strongly on the vertical chromaticity, the beam current and the number of bunches.
- For a 45 bunch train, the HT lines have a maximum power around bunch 30; the line power is reduced for later bunches.
- There is a weak dependence of the onset of the HT lines on the synchrotron tune, the single-bunch vertical emittance, and the vertical feedback. The relatively weak dependence of the HT line onset on the single-bunch vertical emittance is contrary to expectations for the electron cloud effect. It is possible that, due to incoherent emittance growth along the train, the vertical emittance of the bunch at which the instability starts is larger than the single-bunch vertical emittance.
- Under identical conditions, HT lines also appear in electron trains, but the onset is later in the train, and develops more slowly, than for positrons. The HT excitation for electrons may be due to the broadband impedance of the ring.
- Under some conditions, the first bunch in the train also exhibits a head-tail line ($m = -1$ only). The presence of a "precursor" bunch can eliminate the $m = -1$ signal in the first bunch, and also leads to the onset of the HT lines at a later bunch in the train. The implication is that there is a significant cloud density near the beam which lasts many turns. Indications from RFA measurements and simulations indicate this "trapped" cloud may be in the quadrupoles and wigglers.
- There is a strong dependence of the HT line structure observed on last bunch in a 30 bunch train, as a function of the current in that bunch. But the frequency of the vertical betatron line of this bunch is only very weakly dependent on the current in the bunch.
- We have made preliminary measurements of damping rates of single bunches in 30 bunch trains. A more comprehensive set of measurements in the future will shed more light on the effective electron cloud impedance.
- Future work will include more checks for systematics (looking at different BPMs, for example), as well as measurements at different bunch spacings and beam energies.

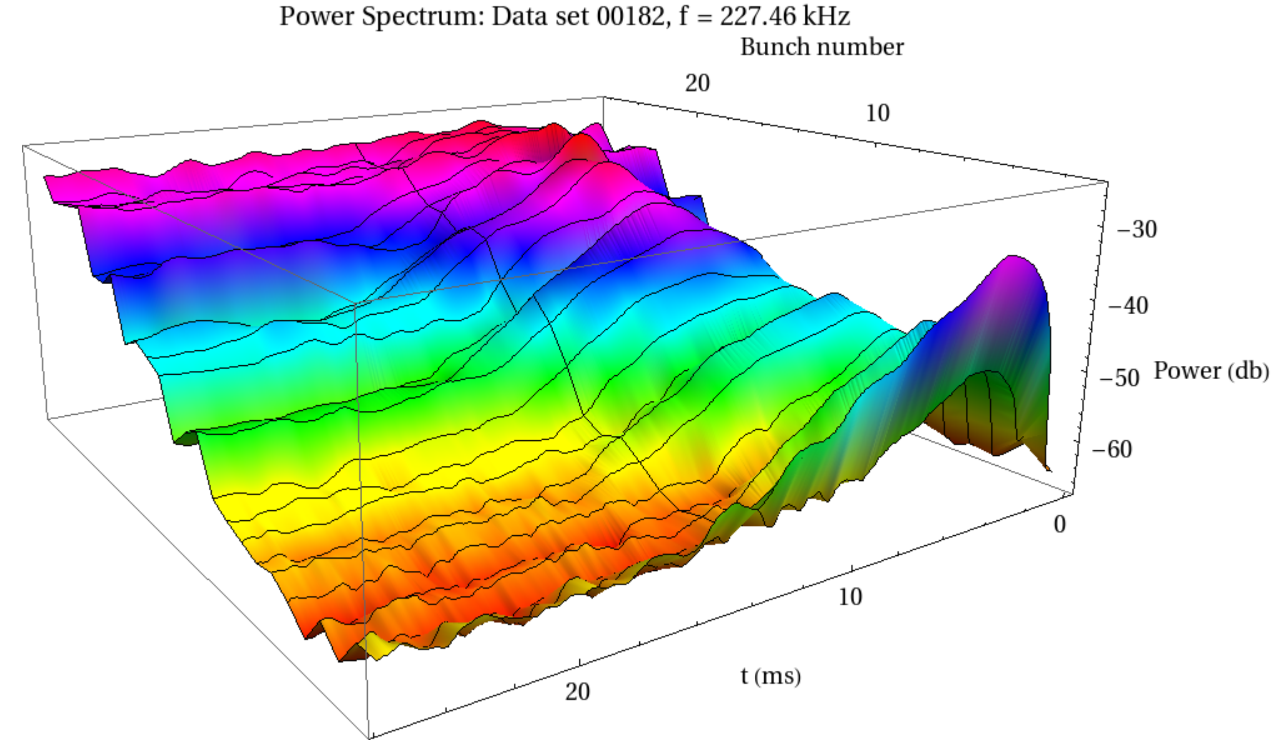

Figure 32: Data set 182: Grow-damp measurements for $m = 0$ mode. Chromaticity: (H,V) =(1.28,2.39). Bunch current = 0.72 mA

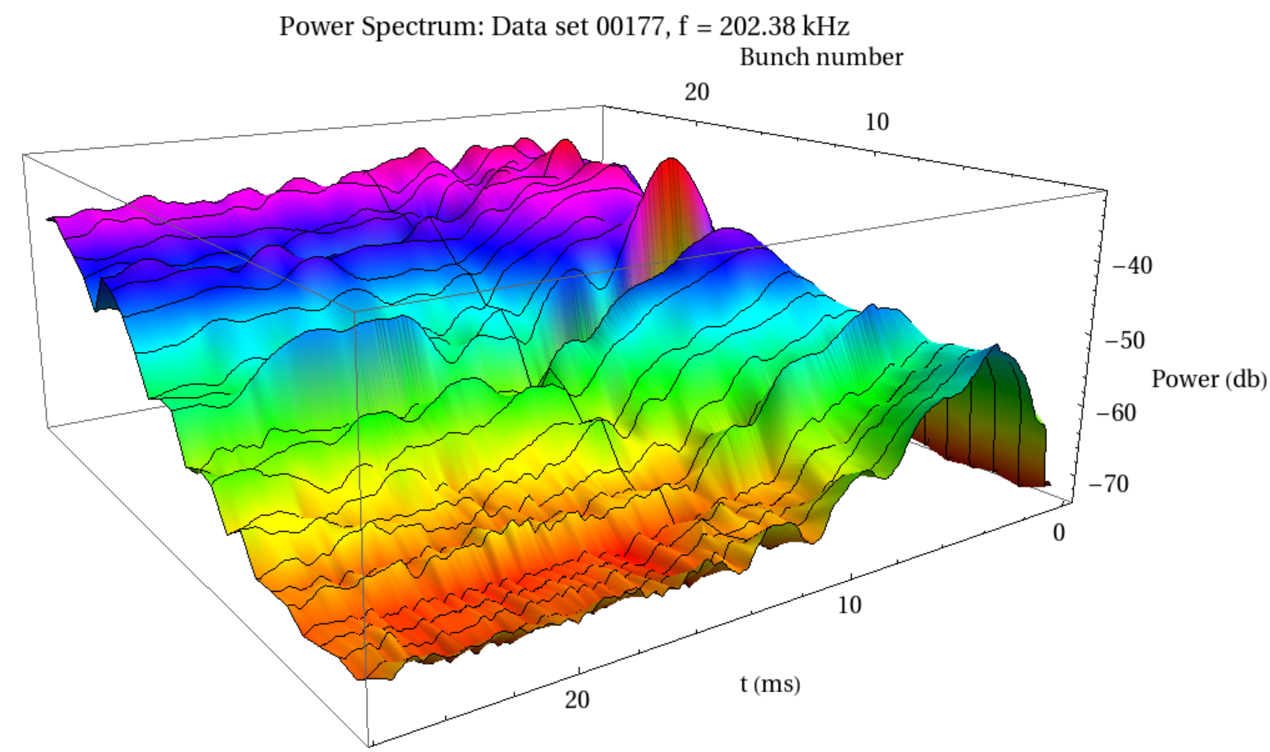

Figure 33: Data set 177: Grow-damp measurements for $m = -1$ mode. Chromaticity: (H,V) =(1.28,2.39). Bunch current = 0.75 mA

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