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Set-up of PEP-II Longitudinal Feedback Systems for Even/Odd Bunch Spacings*

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Abstract

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Set-up of PEP-II Longitudinal Feedback Systems for Even/Odd Bunch Spacings

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Abstract. Feedback systems installed for control of coupled-bunch longitudinal instabilities in PEP-II collider have been designed to process bunch data at one half of the ring RF frequency. As a result these systems are ideally suited for controlling ring fills where only even or only odd RF buckets are populated (even bunch spacings). However in the operation of PEP-II per bunch charge considerations require fill patterns that alternately populate even and odd buckets. In this note we present a technique that allows to use existing hardware to provide feedback control of all bunches in such fills.

INTRODUCTION

PEP-II is a collider comprised of two circular accelerators of differing energies, Low Energy Ring (LER) and High Energy Ring (HER) [1, 2]. Both rings operate above coupled-bunch instability thresholds at the design currents. Feedback systems are required to stabilize the beams in transverse and longitudinal planes [3, 4]. Both rings have a 476 MHz RF frequency which corresponds to a bucket spacing of 2.1 ns. The operation was planned around filled bucket spacings of 4.2 ns or every other RF bucket. In order to reduce the digital signal processing load and analog bandwidth the longitudinal feedback systems were designed to operate at a 238 MHz sampling frequency (one half of the RF).

The operation of a collider is driven by luminosity considerations. Among many factors affecting the luminosity is per bunch charge. During the operation of PEP-II the combination of operating current and optimal per bunch charge made fill patterns with 6.3 ns (every third bucket) and 10.5 ns (every fifth) bunch spacings desirable. In their initial configurations the longitudinal feedback systems could not control fill patterns where both even and odd RF buckets were populated (mixed fills). A modification of the design has been made to address that problem. Here we will describe the design changes required, present corrected beam timing procedures and provide experimental results for the new mode of operation.

There are three signal processing components involved in controlling unstable motion: front-end detection and sampling, filtering by digital signal processors (DSPs), and kick signal generation in the back-end. These components are illustrated in Fig. 1. In order to

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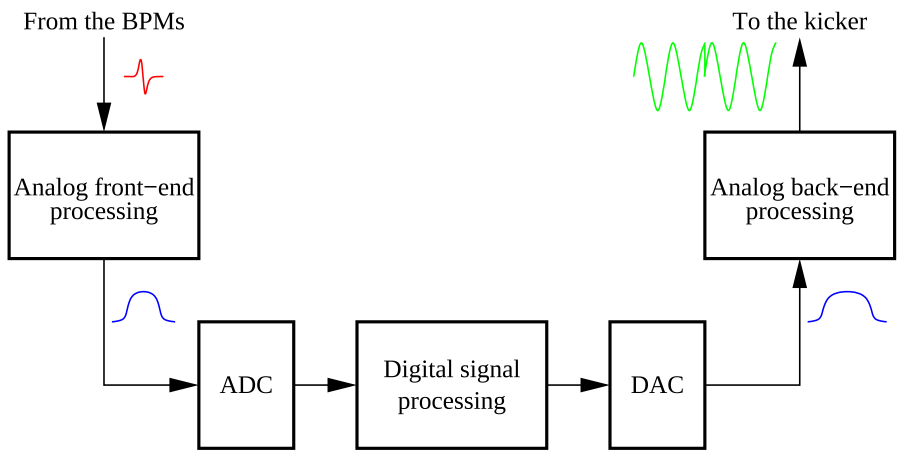

FIGURE 1. Block diagram of the PEP-II longitudinal feedback system

support mixed fills signals from both even and odd buckets must go through the signal processing chain and the kicker signal has to be correctly aligned with the passing bunch. Let's start the discussion from the front-end.

FRONT-END SIGNAL PROCESSING

Analog front-end processing of the longitudinal feedback system is designed to measure time of arrival of each bunch relative to the RF master oscillator clock. This is done using a phase detector operating with the master oscillator derived carrier at $6 \times f_{rf}$. The bunch-induced signal on the BPM output is a very short differentiated pulse. If such a pulse is used as an input to the phase detector, the output signal will be also a short baseband pulse. As a result sampled signal will be very sensitive to both pulse and clock timing. In order to avoid this problem in PEP-II the longitudinal feedback systems use a comb generator filter. In response to a BPM output pulse this filter produces a burst of pulses spaced at $T_{rf}/6$. When such a burst is phase detected baseband signal has a rectangular envelope with duration equal to that of the input burst [5]. Figure 2 shows the front-end block diagram.

Originally both PEP-II longitudinal systems were equipped with 4-tap comb generators that resulted in a baseband pulse of 1.4 ns duration. A timing diagram using such comb generators is given in Fig. 3. By comparing the baseband phase signal with the ADC sampling clock we determine that only even or only odd buckets can be sampled for a fixed clock.

The comb generator design allows one to stretch the detected pulse. If we lengthen the baseband pulse to span 2 RF buckets ($2.1\ ns < T_{pulse} < 4.2\ ns$), the ADC clock can be set up to sample both even and odd buckets. This arrangement is illustrated in Fig. 4 for a 10-tap comb generator. In this case the pulse is 3.5 ns long. If for even buckets we put the sampling clock within $T_{offset} < 1.4$ ns of either rising or falling edges of the pulse, odd buckets will be sampled within $T_{pulse} - T_{rf} - T_{offset} = 1.4\ ns - T_{offset}$ of the

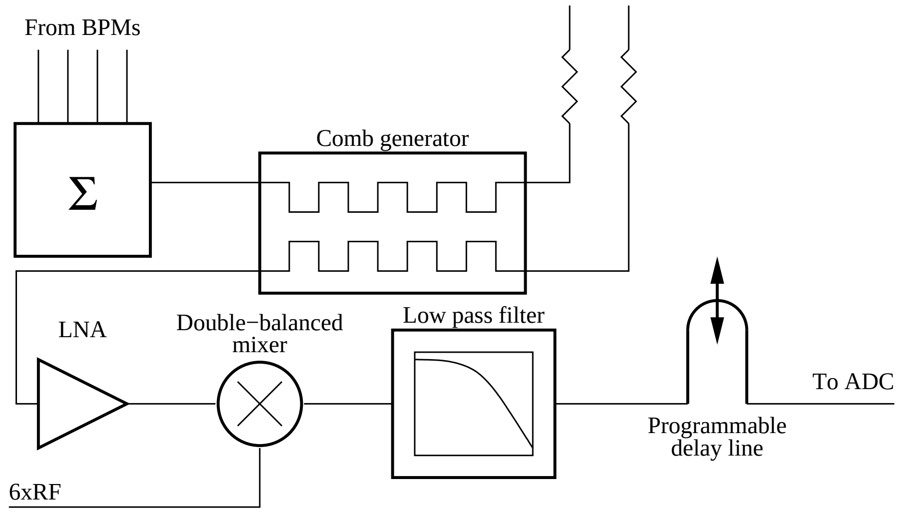

FIGURE 2. Block diagram of longitudinal front-end analog processing

opposite edge. To minimize timing jitter sensitivity we set $T_{offset} = 700\ ps$.

We can arbitrarily select whether to sample filled even buckets near the front or the tail of the pulse. However that choice, as we will see later, affects set up of the back-end. In addition, examining Fig. 4 we see, that for the timing shown bucket 3 is sampled by clock pulse 1. If even buckets are sampled near the front of the pulse, bucket 3 gets sampled by clock pulse 2. This sample shift would not affect feedback processing in these bunch-by-bunch feedback systems with independent digital signal processing for each bunch. However analysis of beam data acquired by the DSPs is dependent on which sampling model (pulse front or tail) is chosen. In order to eliminate ambiguity we've chosen in

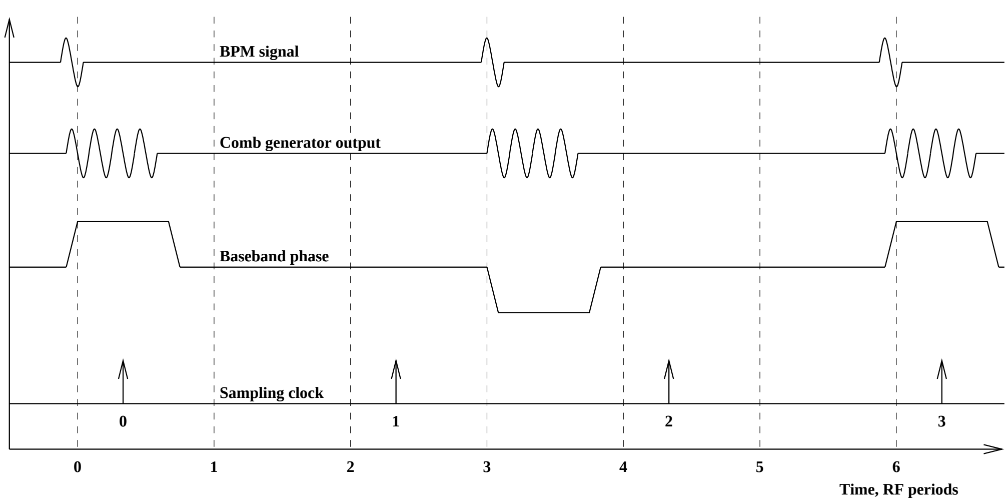

FIGURE 3. Timing with 4-tap comb generator. The top trace shows BPM signals for 3 bunches in the every third bucket fill pattern. Dashed lines show ideal synchronous times, bunches 0 and 6 arrive early while bunch 3 is late.

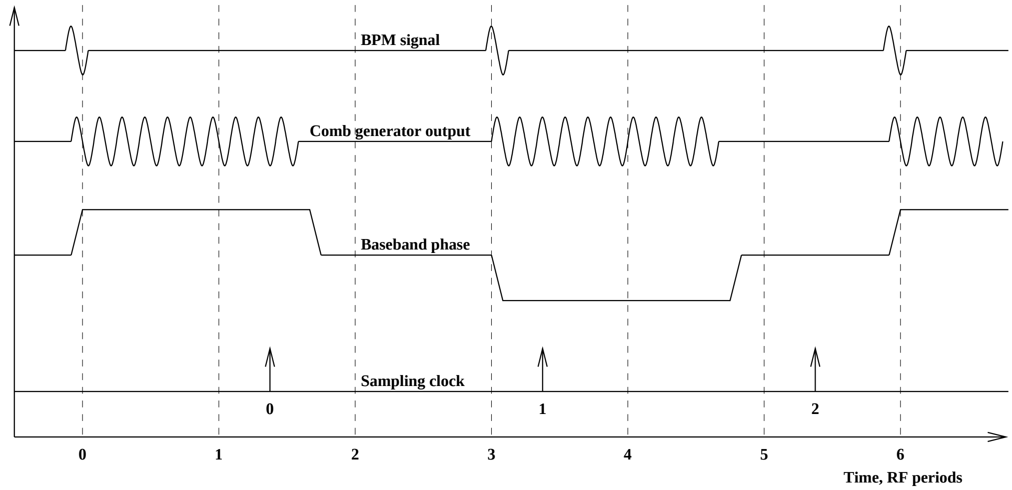

FIGURE 4. Timing with 10-tap comb generator.

PEP-II to sample even buckets at the tail of the pulse.

There are several trade-offs in mixed fill pattern sampling with a long comb generator. First of all, the longer baseband pulse increases coupling between the neighboring bunches. In an ideal system with fast pulse rise and fall times there would be no coupling for pulse lengths below 4.2 ns. However due to ringing in RF components (such as the low-pass filter) baseband pulse can last longer than the length of the comb generator burst. The coupling is worst at the minimal bunch spacing of 4.2 ns. Since the pulse is lengthened by a ringing tail, coupling is most significant for all odd bucket fill patterns. Another negative effect comes from tap spacing errors in the comb generator. If tap spacing is different from nominal $T_{rf}/6$, frequency of the resulting burst is offset from $6 \times f_{rf}$. Consequently detected phase pulse will ride on a slope. Since for mixed fill patterns we sample the pulses at different points for even and odd buckets, the bunch signals will have differing DC offsets. Even though overall DC offset is rejected by the phase servo loop in the feedback front-end, these even to odd bucket offsets cannot be easily compensated.

DSP FILTERS AND POST-PROCESSING

The feedback processing is done on a bunch-by-bunch basis. The harmonic number of PEP-II is 3492 and so the feedback system acquires $3492/2 = 1746$ bunch samples per revolution. These bunch signals are downsampled and processed independently from each other. Thus, as long as the bunch phase signal is properly sampled, it is processed in the same manner within any of the 1746 processing channels.

However post-processing of the data acquired by the feedback system does depend on the actual fill pattern. As shown in Fig. 4 the signal from filled bucket 0 or 1 appears in processing channel 0. In order to accurately extract modal information from the bunch-by-bunch time-domain record we need to know whether even or odd bucket is filled. This

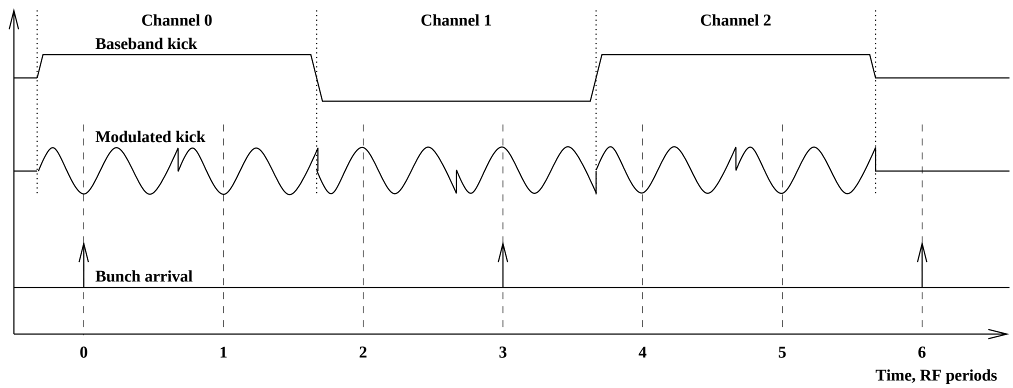

FIGURE 5. Back-end kick signals and timing to the bunch arrivals

information is not present in the data, therefore knowledge of the fill pattern is needed for proper signal reconstruction. Once the fill pattern is known it is easy to determine RF bucket to feedback processing channel correspondence. For front-end timing setup described in section bucket and channel numbers are related as follows:

$$N_{channel} = \lfloor N_{bucket}/2 \rfloor \tag{1}$$

BACK-END SIGNAL PROCESSING

The correction values computed by the DSPs are converted into a baseband analog signal using a D/A clocked at $f_{rf}/2$. The D/A output is then a series of 4.2 ns long steps. In the frequency domain most of the power is in the DC to $f_{rf}/4$ band. The longitudinal feedback kicker for PEP-II is designed with center frequency of $9f_{rf}/4$. Therefore the baseband output of the D/A is mixed with a carrier frequency to place the power within kicker bandwidth. A carrier signal at $9f_{rf}/4$ undergoes a 90 degree phase shift over one RF period. If bunch 0 is timed for maximum positive kick, bunches 1 and 3 will arrive at zero crossings while bunch 2 will see negative kick. To avoid this in PEP-II longitudinal feedbacks phase of the carrier is shifted by -90 degrees every RF period using quadrature phase shift keying (QPSK).

In this discussion we will consider the bunch passage time through the longitudinal kicker to be short relative to the carrier wavelength. PEP-II kickers have three field gaps spaced at 1/4 carrier wavelength. However we can model these as a single short (broadband) gap in combination with a bandpass kicker transfer function. When the bunch passes through the gap it samples the kick voltage. In order to maximize the effect, the kick has to be timed so that a bunch samples the peak of the waveform. As the single-bunch kick is 4.2 ns long there are multiple peaks that can be synchronized with the beam. However, the requirement to affect both even and odd RF buckets restricts the timing. In Fig. 5 waveforms of the back-end signals are shown. Our goal is to chose a kick timing relative to the beam so that both buckets 0 and 1 would sample peaks of the channel 0 kick waveform. There are 5 possible timing settings. However, in order to

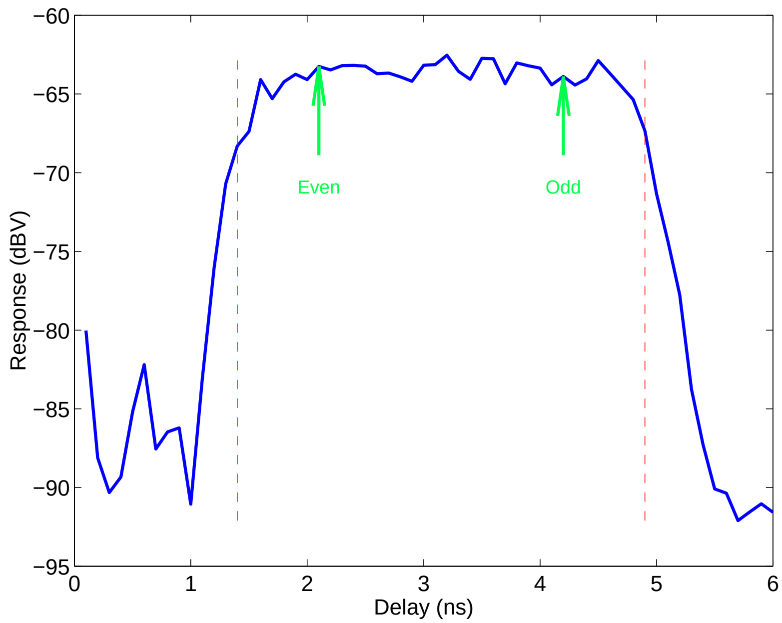

FIGURE 6. PEP-II LER front-end timing sweep. Approximate extent of the phase detector output pulse is indicated by dashed vertical lines. The "even" arrow indicates where the pulse from an even filled bucket is sampled by the ADC, while "odd" pointer shows the sampling for the odd bucket.

minimize interbunch coupling we try to use the peaks closest to the burst center point. For the carrier phasing shown in Fig. 5 there are two timing settings which place either the even or the odd bunch closer to the center point. The choice between the two settings is arbitrary.

It is interesting to note that both in the front-end and the back-end we are dealing with sampling of a finite-duration pulse. In the front-end, the ADC clock samples the baseband phase while in the back-end the bunch samples an amplitude-modulated QPSK carrier. However for the front-end setup where ADC samples the tail of the pulse we have to configure the back-end so that the bunch samples the head of the kick pulse.

EXPERIMENTAL RESULTS

In this section we will describe the procedures for setting up the correct front-end and back-end timings and present experimental data for feedback control of even/odd filling patterns. The front-end timing is controlled by by the setting of the programmable delay line. The delay line allows one to adjust the placement of the phase detector output pulse relative to the ADC clock. The clock signal is locked to the ring master oscillator and for fixed RF voltage phase remains in a constant relation to the beam phase.

In order to determine optimal setting for the front-end delay line an automated timing utility is used. First a single bucket in the ring is filled to nominal per bunch charge. The feedback system is set up to deliver a back-end correction signal for only one channel - the channel that must sample the filled bucket. Then under program control the delay

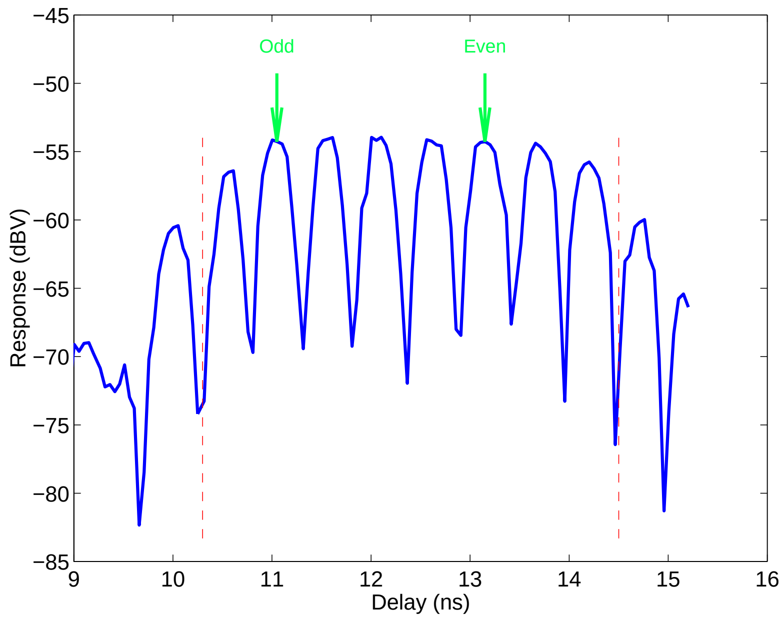

FIGURE 7. PEP-II LER back-end timing sweep. The dashed lines show the DAC pulse length of 4.2 ns. This pulse is stretched due to the bandlimiting in the kicker. The "even" arrow indicates the point where the even bucket samples the kick waveform.

line is swept through a range of values and at each setting the baseband spectrum of the DAC output is measured. Due to the RF noise excitation the beam oscillates at the synchrotron frequency. That motion is amplified by the feedback filter and allows the determination of the amplitude sampled by the ADC. By selecting a spectral component at the synchrotron resonance peak we obtain sampled signal amplitude versus delay as shown in Fig. 6. Note that the delay axis goes in the opposite direction from the time axis, that is larger delay setting corresponds to sampling the earlier part of the pulse. Since we decided to sample the even buckets towards the tail of the pulse the "even" timing arrow is placed closer to the left edge of the delay sweep.

A similar automated procedure is used to set the back-end delay line. In this case with a single bunch in the ring we program the DSPs to produce sinusoidal excitation at the synchrotron frequency in a single channel. As the delay line is swept through the region of interest at each setting we record the spectrum of the beam via the phase-detector output. When the kicker burst is correctly aligned with the beam the driven motion is maximal. By plotting the signal amplitude at the synchrotron frequency against the delay setting we get the magnitude response of the kicker as illustrated in Fig. 7. Here two response lobes 2.1 ns apart are selected for even and odd bucket timing. As expected the positions of even and odd buckets are reversed relative to the front-end sweep.

After the optimal timing settings are determined we are able to fill the rings in the even/odd fill patterns, for example every third bucket. After filling the LER to 800 mA we recorded beam data in the closed-loop feedback configuration to verify the system stability. In Fig. 8 the RMS amplitudes of the recorded data are show for the first 12 DSP channels. Empty channels show RMS motion of 1 ADC count while the

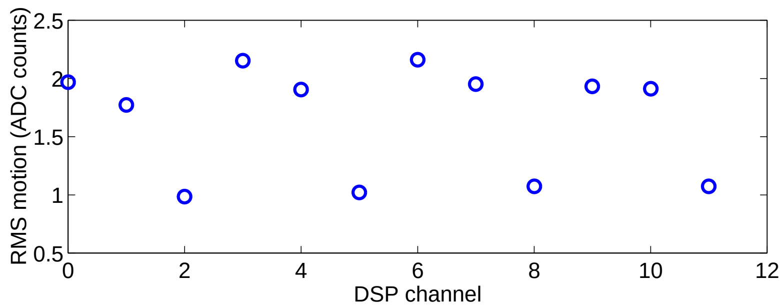

FIGURE 8. RMS of the beam data recorded by the DSPs. Bucket 0 is sampled by channel 0 while bucket 3 signal is in channel 1.

channels sampling filled buckets show 2 counts. Since the front-end is timed to sample even buckets near the tail of the pulse we can reconstruct the underlying fill pattern unambiguously.

In Fig. 9 average amplitudes of the coupled-bunch eigenmodes are shown. These values are obtained by transforming the abovementioned data set to the eigenmodal basis. Since the measurement was made in the closed-loop configuration we obtain the steady-state modal amplitudes. Most of the eigenmodes are damped by the feedback to the noise floor with the notable exception of eigenmode 0 oscillating at 0.09 degrees. This lowest-frequency mode is excited by the RF noise from the klystron high-voltage power supplies. The fill pattern has periodic minigaps which act to alias mode 0 every 72 revolution harmonics.

SUMMARY

Modification of the comb generator length in combination with proper front-end and back-end timing procedures described here have enabled PEP-II to use the mixed even/odd ring filling patterns required to optimize luminosity. Under these conditions we have demonstrated feedback stabilization of longitudinal coupled-bunch instabilities at the design beam currents.

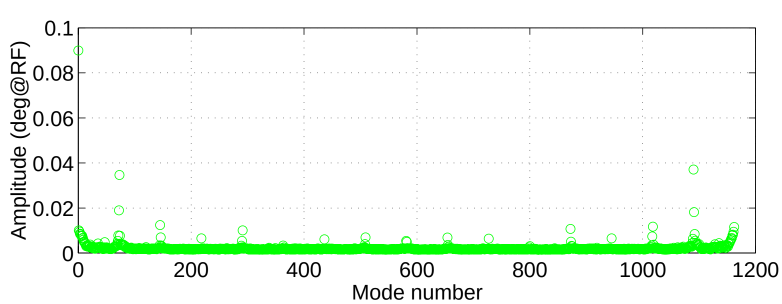

FIGURE 9. Average modal amplitudes in the LER at 800 mA

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