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HARMONIC BASED BEAM POSITION MEASUREMENTS ON DEBUNCHED BEAMS

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Abstract

In some accelerator environments, e.g. in linear accelerator (LINAC), the beam position is measured with a BPM operating at one particular strong harmonic component present in the beam signal. This approach has limitations once the beam gets debunched and the harmonic components drops. Nevertheless, from a signal processing point of view the signal-to-noise ratio can be still acceptable with highly debunched beams, leading, in principle, to a reasonable, even if degraded, position measurement. A simplified beam transport model developed for the CERN BI transfer line between LINAC4 and the PS Booster demonstrates, that in some case, the harmonic component cannot be used anymore for position measurement despite the fact it is still significative in amplitude.

INTRODUCTION

Beam Position Monitors (BPMs) are one of the most used instruments in a particle accelerator. Their main functionality is the monitoring of the beam trajectory in linear accelerators (LINACs) and transfer lines and the closed orbit in circular machines. In addition, BPMs can provide other beam parameters such as beam intensity, kinetic energy and longitudinal distribution.

The basic idea of most BPM is to measure the image current flowing on the conducting beam pipe [1]. Typically, for the estimation of the transverse beam position, a set of two opposite electromagnetic pickups or electrodes is used, for the horizontal and the vertical plane.

Different types of BPM pickups exist and, depending on the machine and the required measurements, a specific BPM type is chosen accordingly.

The signals at the BPM electrodes can be degraded by electromagnetic interference of nearby devices. Also, depending on the BPM type, its signal can be corrupted by beam loss and secondary emitted particles. If the beam has a fixed pattern, this feature can be exploited in order to mitigate these effects. For example, in LINACs, where the acceleration process bunches the beam at a rate defined by the frequency of the accelerating cavities, the signals present strong components at the harmonics of the RF frequency. In this case, the receiver could be tuned at a single harmonic and use the envelope of the received signal for the position estimation.

CURRENT HARMONICS OF A GAUSSIAN BEAM

Assuming a train of bunches with a Gaussian longitudinal distribution [2], with individual bunch charge q, spaced by $T=1/f_{RF}$, the beam current intensity is

$$I(t) = \frac{q}{\sqrt{2\pi}\sigma} \sum_{n=-\infty}^{+\infty} e^{-\frac{(t-nT)^2}{2\sigma^2}} \tag{1}$$

and the harmonics can made explicit by expanding the summation using the cosine series§

$$I(t) = I_0 \left[1 + \sum_{n=1}^{+\infty} K_n \cos\left(\frac{2\pi n t}{T}\right)\right] \tag{2}$$

where I_0 is the DC beam average current and

$$K_n = e^{-\left(\frac{\omega_{RF}\cdot n\cdot\sigma}{\sqrt{2}}\right)^2} \tag{3}$$

CURRENT HARMONICS OF A NON-GAUSSIAN BEAM

In the case of non-Gaussian longitudinal distribution, the same expansion in cosine series as with the Gaussian beam can be made, but with the difference that one or more harmonics can vanish and hence cannot be used.

For example, a train of rectangular square bunches of duration W and period $T=1/f_{RF}$ is described by Eq. (2) with

$$K_n = sinc\left(\frac{n\pi W}{T}\right) = \frac{\sin\left(\frac{n\pi W}{T}\right)}{\frac{n\pi W}{T}} \tag{4}$$

vanishing for pulse duration W multiple of T/n [2]. This means that for specific bunch lengths the signal from the electrodes of a BPM pickup will not have the f_{RF} harmonic component

In practice this condition can be reached along the transfer line of LINACs where the beam energy spread associated with the non-relativistic beam energy, and space charge effect, results in increasing long bunches. This debunching process also modifies the shape of the longitudinal bunch distribution so that the harmonic vanishing can happen even if a Gaussian beam is injected into the line.

Furthermore, a so called "de-buncher cavity" can be present at the end of a LINAC in order to provide the energy spread demanded by the downstream machine, which causes the vanishing of the harmonic content at a range of locations depending on the settings of this cavity.

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§ Cosine series can only be used for even functions but it's not reducing generality

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CERN LINAC4 TO PSB TRANSFER LINE CASE

The CERN H- transfer line from LINAC4 to PS Booster (PSB) is equipped with 13 dual plane (2+2 electrodes) stripline pickups. The BPM system operates at the 352.2 MHz LINAC4 frequency and a (de)buncher cavity is located at the beginning of the line.

LINAC4 produces beam in pulses at a rate of 1.2 seconds. The pulse length is in the order of several hundreds of microseconds. The downstream PS Booster is made of four vertically stacked synchrotron rings. Each LINAC4 pulse is composed of four time slices sequentially distributed to the four PSB rings at the end of the transfer line [3].

The BPM system reports four beam positions representing the average beam position along each time slice that is eventually sent to the destination PSB ring (Fig. 1).

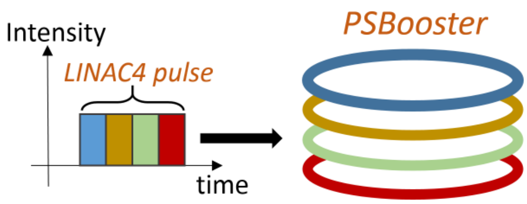

Figure 1: PS Booster injection scheme.

The setting of LINAC4 and the transport line are unchanged along the pulse, so, in principle, each slice should behave identically. When the (de)buncher cavity is not active (natural debunching) or is set to rebunch the beam, the BPM system works properly along all the beam line with stable reported positions. But if the (de)buncher cavity is active increasing the beam energy spread and debunching the beam, the measured positions in a specific region of the line are showing degraded performance from shot-to-shot and slice-to-slice variations.

By observing the BPM sum signal, representing the intensity of the 352 MHz component of the beam current at the BPM location, a notch is observed in the region where bad positions are reported (Fig. 2). The position instability could be caused by a too low signal-to-noise ratio, but this seems to be not the case as the observed position fluctuations are not compatible with the measured signal-to-noise levels.

SIMPLIFIED BEAM TRANSPORT MODELLING

In order to understand and explain the observed behaviour, a simplified beam transport model of the (de)buncher cavity and the following transport line has been written in Python. The assumptions of this model are:

1) Perfectly collimated beam moving ballistically straight with no magnetic fields
2) Zero transit time in the cavity.
3) Pure transverse electromagnetic field generated by the beam.
4) Constant energy spread along the line (no space charge or other collective effects).
5) Linear BPM response

The initial longitudinal bunch shape and energy spread are input parameters that originated from other simulations and/or specific measurements.

Despite several simplifying assumptions, the results are in good agreement with the measurements and with the precise simulation made with TraceWin (Fig. 2) [4].

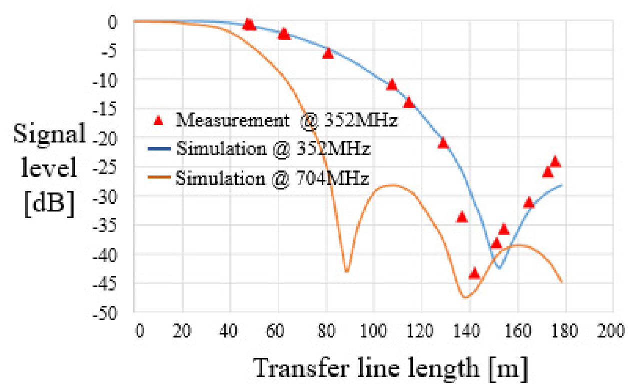

Figure 2: Signal level along the line for debunched beam.

The measured signal intensity notch at the location of about 140 m downstream the transfer line could be explained by the shape of a single bunch transported along the line. Figure 3 shows the expected longitudinal bunch distribution, which differs from a perfect Gaussian shape. Even in case of a Gaussian distribution at the beginning of the line, the beam would lose such a distribution while moving along the line, with the consequent possibility of developing intensity notches at specific locations depending on the harmonic component used for measurement.

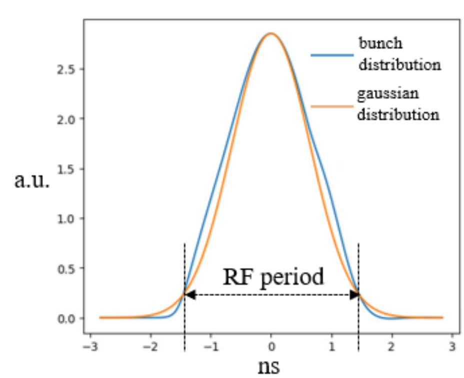

Figure 3: Longitudinal distribution of a transported bunch.

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POSITION MEASUREMENTS IN THE REGION OF THE NOTCH

In principle, any higher harmonic of the beam could be used by the BPM system, but in practice, for the CERN LINAC4 to PSB transfer line only the first (352 MHz) and the second harmonic (704 MHz) have a reasonable signal level following the losses of the long cable (>100 m) running from the tunnel to the electronics.

From the simulation in Fig. 2, the notch of the second harmonic is slightly shifted from the notch of the first harmonic. A comparison between the vertical positions measured at the first (Fig. 4) and at the second harmonic (Fig. 5) is made for a BPM pickup at a location close to the first harmonic notch of the transfer line at ~140 m.

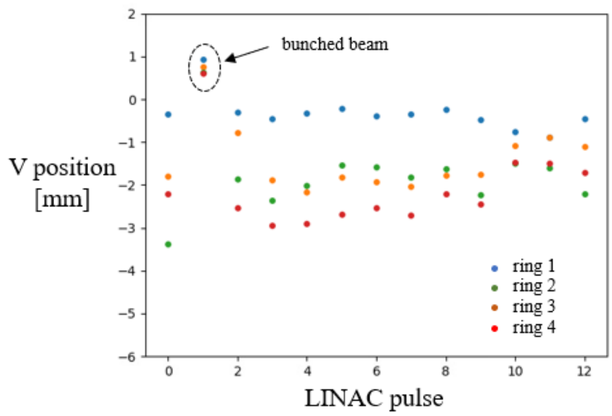

Figure 4: Debunched beam measured at 352 MHz.

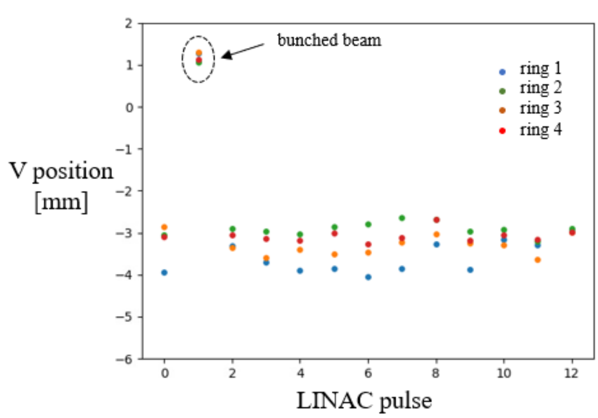

Figure 5: Debunched beam measured at 704 MHz.

The vertical position of the four slices injected in PSB (Fig. 1) for multiple LINAC4 pulses is plotted along with the pulse index in the horizontal axis. Measurements were performed simultaneously for the first and the second harmonic by splitting the electrode signals. To be noticed that the pulse #1 was a bunched beam and the position at both harmonics converges to a similar value for all slices which is the expected behaviour also for the debunched beam pulses. The different absolute position between the bunched and debunched beam pulses is not unexpected because of the different beam optics applied in the line for the two cases.

Using the second harmonic, the position stability slice-to-slice and shot-to-shot showed an improved reproducibility and uniformity, which is expected from the fact that the pickup location is not as close to a notch as for the first harmonic for this specific setting of the debuncher cavity. However, the results are still not satisfactory.

Since the LINAC4 beam is chopped at a 1 MHz rate (Fig. 6), a position measurement exploiting this feature, that will be called low frequency (LF), was used to confirm the artefacts of the high frequency (HF) measurements, based on the harmonics of the bunching frequency (Fig. 7).

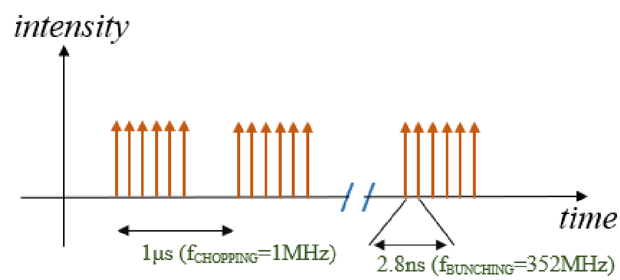

Figure 6: LINAC4 beam structure.

In this case the horizontal beam positions at LF and at 352 MHz (HF) were measured at the same time by splitting the electrode signals. For the LF measurement the electrode signals were low-pass filtered with 20 MHz cut-off frequency to completely remove the bunching frequency components and keep the chopping pattern contribution.

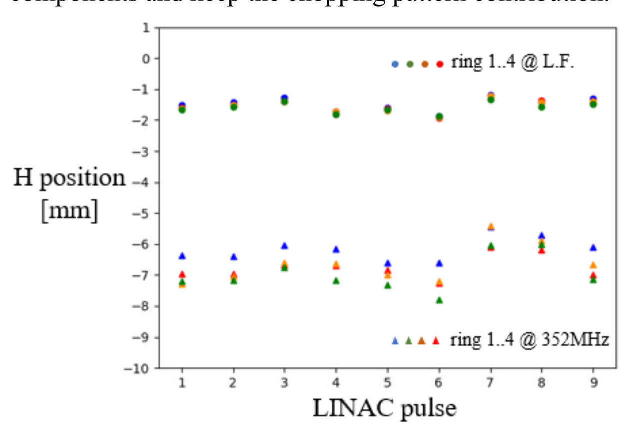

Figure 7: Debunched beam measured at LF and 352 MHz.

The improvement in the position stability is evident and coherent with the results in case of bunched beam in terms of shot-to-shot and bunch-to-bunch stability, proving the inconsistency of the debunched beam position measured using the harmonics of the bunching frequency at this location.

To confirm the consistency of the LF measurement, also bunched beam was measured simultaneously at LF and at 352 MHz, giving, as expected in this case, reported beam positions in very good agreement (Fig. 8).

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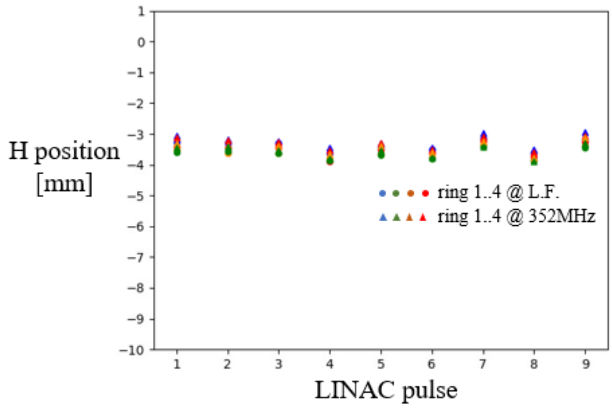

Figure 8: Bunched beam measured at LF and 352MHz.

Using the simplified model described before, an off-center beam position is calculated in the region of the signal intensity notch, depending on the transverse beam position along the bunch used as simulation parameter. Variation of this parameter along the LINAC4 beam pulse and from pulse to pulse could explain the measured fluctuations. However, this mechanism has not been verified by measurements or more comprehensive simulations.

CONCLUSION

In case of highly debunched beam, the use of BPM operating at harmonic components present in the signal must be carefully evaluated since the signal levels may have notches at specific locations along the beam line. In this region at the CERN LINAC4 to PS booster transfer line, the BPM system, both operating at the first and second harmonic of the LINAC, shows unacceptable fluctuations of the reported beam position.

Using a different harmonic can be in principle beneficial at some specific location, but in general more notches could appear along the line. This was tried and indeed did not solve the issue in the specific case described.

The presence of a low-frequency modulation (beam pulse chopping), with low in the sense that the period is much longer than the bunch distance, could potentially solve this accuracy degradation as demonstrated by initial measurements.

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