TOPOS Debugging: Issues and Outlook

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November 23, 2014

1 Introduction

TOPOS is a digital Tune, Orbit and POSition measurement system which is currently under operation at GSI [1]. TOPOS can provide bunch-by-bunch position from all 12 BPMs simultaneously during the full acceleration cycle in a continuous mode (i.e automatic acquisition from cycle to cycle). It can also provide digitized raw BPM signal from all 48 pick-up (4 per BPM) electrodes for ≈ 300 ms. TOPOS is designed to work with high dynamic range of beam current. TOPOS is an extremely important tool for accelerator optimisation and operation and has been extensively utilized for studying beam dynamics [2, 3, 4, 5]. However, since its commissioning in August 2012, TOPOS has had few recurring operational issues. This report addresses some of the issues and makes some recommendations for further development of TOPOS.

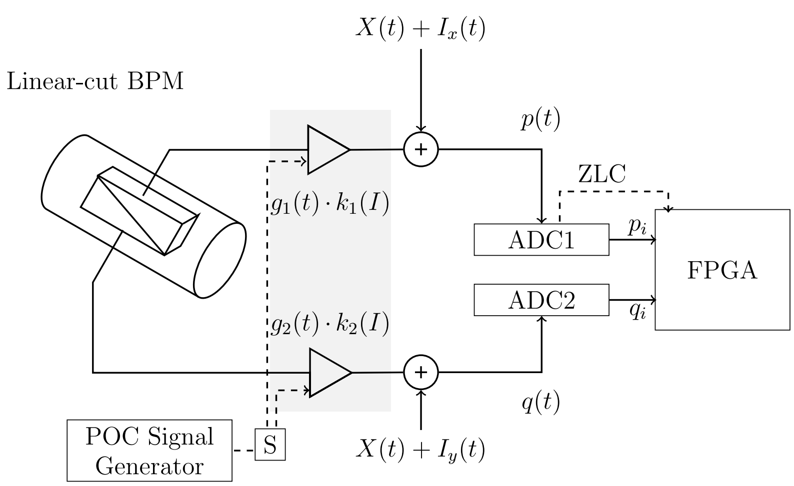


Figure 1: TOPOS acquisition chain and calibration system. The dashed lines correspond to the calibration procedures.

1.1 System details

To understand the nature of problems surrounding TOPOS, the system layout for the acquisition part of TOPOS is shown in Fig. 1. For simplicity, only two electrodes and their amplification chain is considered which is sufficient to highlight all the issues discussed in this report. The frequency response of the opposite pick-up electrodes and subsequent amplifier chains are denoted by the impulse response $g_1(t), g_2(t)$ while the gain of the amplification chains are given by $k_1(I), k_2(I)$. The amplified pick-up signal is digitized by 14 bit 125 MSa/s ADCs. The signal samples thus obtained from the ADCs are fed to an FPGA, where the real-time position value is calculated.

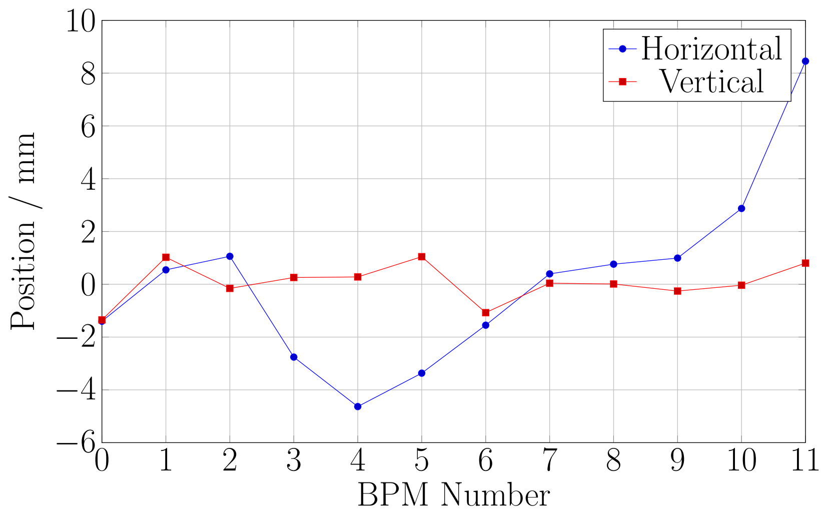


Figure 2: Position offset calibration values at the gain of 20 dB.

The gain $k(I)$ is shown to be a function of input signal amplitude or beam intensity I. Though the amplifier chain is designed to be linear and matched between the opposing channels, temperature variations and time drifts can lead to small gain mismatch between the opposite amplifiers. The gain mismatch between the opposing amplifier chains can lead to significant deviations in position calculated.

To reduce the effect of gain mismatch between opposing amplifiers, position offset calibration (POC) is performed. The POC signal generator generates a bunch like signal which is splitted and fed to the input of opposite amplifier chains. Figure 2 shows the typical position offset values. The calibrated position calculated takes the mismatch of amplifiers into account. Zero line calibration (ZLC) is performed to take the ADC noise into account (Show a screenshot ?). Position offset calibration values are found to be much larger than the accuracy needed for normal operation and the procedure is absolutely necessary for normal SIS-18 operations.

1.2 Issues

Some of the critical operational issues are highlighted below,

- Beam intensity/amplifier gain dependent position movement of upto 2 mm. This problem was identified during a machine development experiment when the effect of tune on closed orbit was being studied.
- Beam based bunch detection for very short bunches or severely distorted bunches has its boundaries. This was observed during the high energy proton beam operation.
- Random Libera(s) still acquire for very long times after the stop acquisition trigger.

2 Position calculation algorithm and system calibration

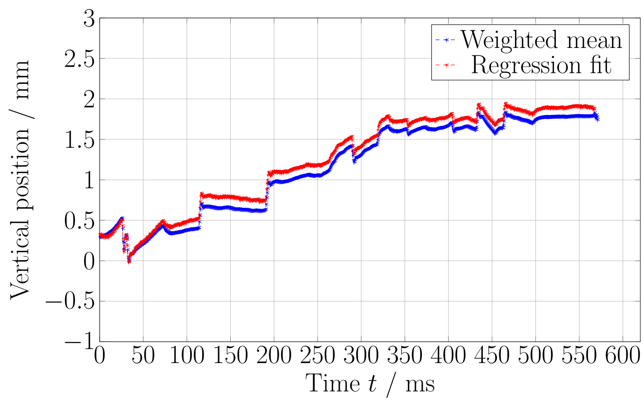
During the machine development studies for beam based detection of magnet alignments, it was found that the beam position moved substantially in dependence of beam losses. Further investigations led to measurements with same intensity, but at different amplifier gain settings and it also gave a noticeable shift of 1-2 mm in beam position. This intensity/gain dependent position leads the system unusable for precise optimization of the machine. The TOPOS system will be used for regular lattice optimization methods such as orbit response matrix or closed orbit feedback systems, where any errors in position calculation will result in wrong lattice information or non-optimized feedback system. General rule of thumb says 10% or beam width, which corresponds to 0.5-1 mm accuracy of the beam position.

The first investigations checked the two major possibilities which lead to these intensity dependent positions,

1. The position calculation algorithm uses a complicated procedure called baseline restoration before doing a weighted mean of difference-over-sum of each sample within the detected bunch. It uses the data between the bunches to restore the "baseline" to zero. In other words, it tries to reconstruct the DC part of the beam which is lost due to high pass frequency response of the pick-up. Although, the procedure is intuitive to understand, the algorithm is non-linear and non-trivial in nature.
2. The mismatch of the amplifier gains to opposite BPM electrodes. This point effectively means that the position offset calibration might not be adequate.

2.1 Implementation and comparison of position calculation algorithms

The digitization of BPM data and the position calculation in the FPGA are the "newer" parts of the BPM system, and were the primary suspect. Therefore an alternate and computationally simpler algorithm, the "regression fit algorithm" was implemented in the FPGA. The results of this algorithm were compared to the baseline restoration with weighted mean algorithm online.



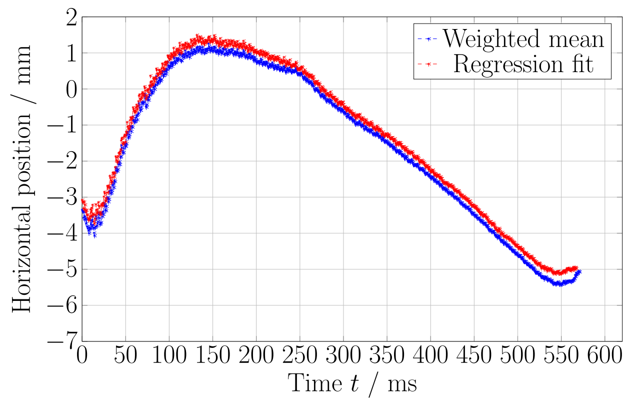


Figure 3: The horizontal and vertical beam position from "weighted mean with baseline restoration" algorithm and "regression fit" algorithm.

The results of the two algorithms were found to be consistent with a systematic bias between then which was predicted in previous studies [2].

The reason for this systematic bias is that, the baseline restoration do not precisely restore the DC part of the beam signal, since baseline itself is a representation of position history of several bunches preceding it. Thus the baseline introduces data dependent bias, and the position calculated minutely depends on the history of position till that point. This bias is measured between 0.2-0.5

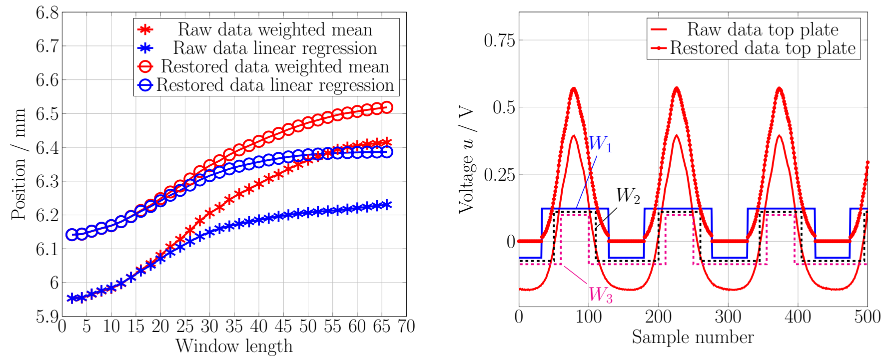


Figure 4: (a) Mean of 500 calculated position values using both algorithms with and without BLR against the window lengths. (b) The marked window lengths (W_1, W_2, W_3) depict how the window length is varied while keeping the center of bunch within the window enclosure.

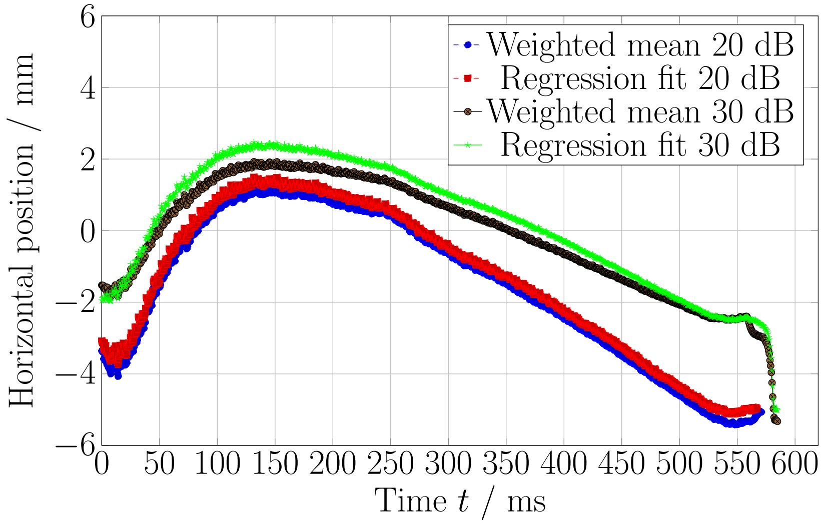
mm. Similar bias was observed between previous position measurement tool POSI and TOPOS[1].

Figure 5 shows the positions at different gain settings for the same beam, when calibration is performed only for 20 dB gain setting. Both algorithms are almost equally affected by the gain setting while maintaining a systematic bias between them. One can also see that the movement of position is much larger in the horizontal plane in comparison to the vertical plane. This hints towards the amplifier gain issues, since the same mismatch in horizontal and vertical amplifier chain will result in larger horizontal position due to lower sensitivity of horizontal BPMs. The ADCs and their ZLC is quite small values independent of gain setting and the algorithms are completely identical for both planes and should result in similar magnitude of errors.

2.2 Response of the amplifiers

The amplifier chain shown in shaded box in Fig. 1 is elaborately shown in Fig. 6. There is a constant amplification of 50 dB, and the attenuators are switched in a certain configuration to provide a dynamic range of 90 dB. The 50 dB amplifiers are switched on all the time, while attenuators are switched based on the gain required. Therefore the gain varies from -40 dB to 50 dB.The noise figure of the system depends on the gain i.e. choice of switched attenuators between Head amplifier and pre-amplifier. The noise figure changes by a factor of ≈ 2 in two extreme amplifier configurations.

As mentioned earlier and shown in Figure 1, the system is calibrated with a fixed amplitude signal generator for mismatch in amplifier gains and the resulting position offset. The calibration can only be performed for the gain settings in the range of 20 dB due to the fixed amplitude input signal. It is assumed that



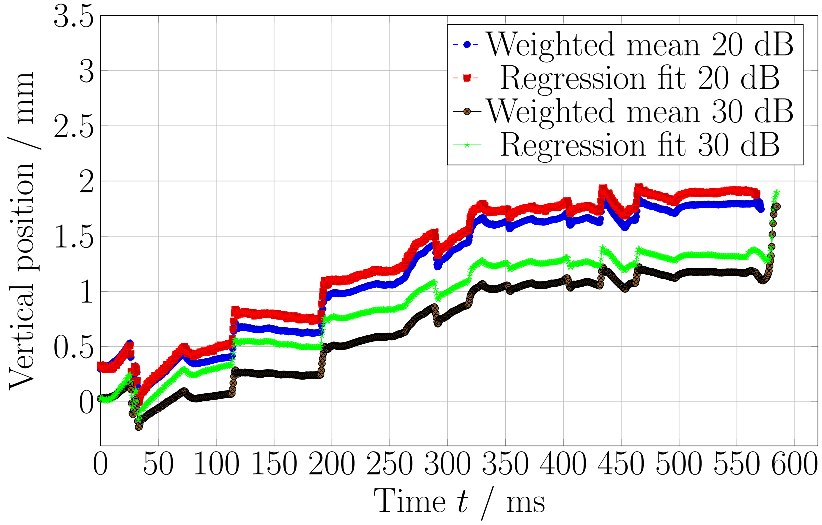


Figure 5: The Horizontal and vertical position calculated by both algorithms at different gain settings for the same beam.

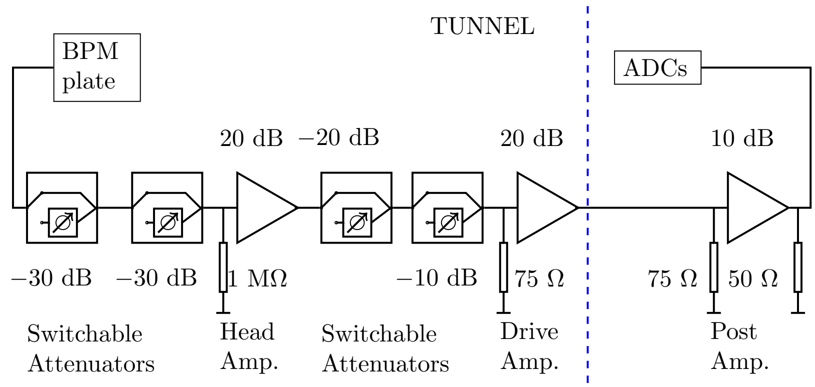


Figure 6: The TOPOS amplifier and attenuator chain.

the calibration performed at two gain settings are valid for other settings. There are two different aspects of mismatched amplifier gain issue with substantially different severity levels.

1. The change in gain settings lead to mismatch of amplifiers.
2. The amplifier gain curve is mismatched for each input voltage amplitude, i.e the amplifier response is non-linear and distinct for each amplifier settings.

In the first case, if we perform a POC at each gain setting, the issue is solved. However, for the second case, a map of the mismatch as a function of input amplitude has to be accurately determined for each gain setting, and it has to be regularly updated.

Let us estimate the position offset for a non-calibrated amplifier which result from a 0.5 dB gain mismatch. The regular difference over sum method uses all the samples within the detected bunch to calculate the position for noise suppression,

$$x, y_{wm} = K_{x,y} \frac{\sum_{i=1}^{N} p_i - q_i}{\sum_{i=1}^{N} p_i + q_i} \tag{1}$$

Where $K_{x,y} = 120, 45$ are the pick-up sensitivity in horizontal and vertical planes. For demonstration, we assume that only a single sample at the peak ($i = peak$) of the bunch is used for position calculation,

$$x, y_{peak} = \frac{p_{peak} - q_{peak}}{p_{peak} + q_{peak}} \tag{2}$$

The pick-ups have a transfer impedance of $\approx 10\ \Omega$ [6]. For a centered beam of peak current with a 5 mA, the voltage developed on the input of amplifier chain is $\approx$ 50 mV. So, the gain setting of 20 dB will give appropriate signal amplitude for 1 Vp-p ADC range.

If we apply Eq. 2 for these signals,

$$x, y_{peak} = K_{x,y} * 50(k_1(I) - k_2(I))/50(k_1(I) + k_2(I)) \tag{3}$$
$$= 140, 45 * (529 - 500/1029) \tag{4}$$
$$= 4.08, 1.25 \tag{5}$$

Thus a small mismatch of 0.5 dB between the amplifier chains k_1 and k_2. This leads to position deviations in horizontal plane as large as 4 mm. The order of magnitude also matches the position offset values shown in Fig. 2. These numbers are quite alarming, if one considers the usage of TOPOS for precise machine optimization, and a very careful calibration procedure should be adopted.

2.3 Miscellaneous results

During the comparison of the two algorithms online, we also observed other properties of baseline algorithm which did not get sufficient attention. The baseline restoration acts as an adaptive filter which suppresses spurious low frequency signals. Here is an example,

Is this unintended filtering good or bad?

3 Timing issues

3.1 Error description

When measuring with TOPOS, there was a problem with the measured acquisition length. This problem showed itself on one or several random BPMs simultaneously, changing from cycle to cycle and concerned all BPMs. When this error occurred, the acquisition length of the affected BPMs was several multiple times longer than the expected acquisition length defined by the TOPOS Timing Settings. This issue was also known as Stop Trigger Error.

3.2 Error cause

The calculation of the timebase of a measurement cycle is done on two concentrator servers which receive data from the BPMs' acquistion electronics (Libera). The basis for calculation is a timestamp (T_{RF}), generated in Libera's FPGA for each bunch.

After diverse simulations and analysis of the FPGA design's signals, it was found out that the error was caused by a missing reset of a certain handshake signal which is responsible for correct handling of the timestamps inside the FPGA. Since calculation of the positions of a bunch lasts longer than multiple periods of the bunch frequency, the T_{RF} for a detected bunch must be stored in a FIFO to join it later together with it's associated position data for transmission to the concentration servers. To get data out of this FIFO a read strobe signal (RSTB) is used which is usually one clock cycle long. The error occurred because the RSTB was not reset after the end of a measurement cycle. If the measurement cycle was finished at the same time as a RSTB was executed, the RSTB stayed active until the beginning of the following measurement cylcle, which always lasts much longer than one clock cycle. This caused the FIFO to be in an undefined state and brought it to deliver wrong timestamps for the upcoming measurement cycle.

4 Bunch based detection

In the figure shown below, TOPOS stops bunch detection with the window length of ≈ 16. In the proton beam time, similar effects were seen with window length of 5-6 samples. These measurements hints towards the limitations of the bunch detection procedure.

- Give the magic numbers of double threshold, and predict its effect on the conditions, when the detection fails.
- For what lengths of a normal bunch, the detection will fail? Example of an abnormal bunch, when the bunch detection will fail and why?
- Explore the possibility of RF based bunch detection.

5 Outlook

5.1 Recommendations

1. Calibration for all possible gains of the amplifiers. One has to use a varying amplitude calibration source for that.
2. What is bunch by bunch position resolution? Since the noise figure varies by a factor of 2, so does position resolution. We should provide a number for different gain settings with the new amplifiers.
3. Investigate the possibility of dispersion compensation and RF based bunch detection as fall back for small bunches and distorted bunches.

5.2 Other ideas

- Phase space reconstruction using bunch to bunch data is very attractive, and provides information about lattice. (Put the phase plots by Christine). Investigate if the synchronism between BPMs is really necessary?

- The raw data tomography from the TOPOS can/should be supplied to Oleksandr for low current tomography. Figures 7 and 8 show two examples of longitudinal phase space reconstruction. Figure 7 uses 300 bunches immediately after injection and Filamentation due to non-adiabatic buncgin is clearly visible. Figure 8 (bottom) shows the longitudinal pahse space 250 ms after injection. The filamentation is smoothed out. Figure 8 (top) shows selective loss/scraping of beam due to periodic crossing of a third order resonance by particles with a momentum in a given range.

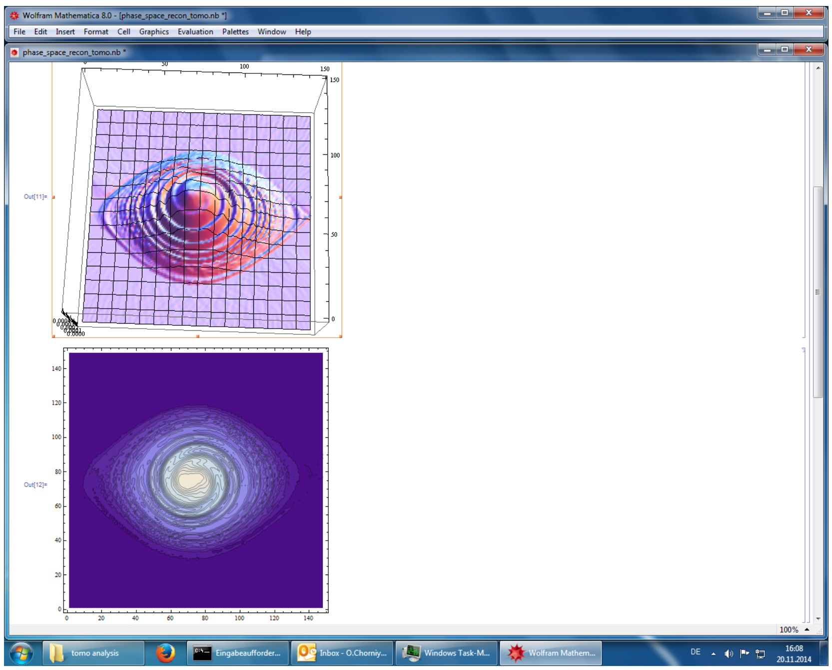


Figure 7: Longitudinal tomography for quickly bunched beam (non-adiabatic bunching) at SIS-18. The filamentation of the particles is clearly visible. Courtesy : O . Chorniy.

6 Appendix

References

[1] K. Lang, "Ein Tune, Orbit und Positions System", GSI group seminar presentation, 2010.

[2] R. Singh, "Tune measurements at SIS-18: Methods and Applications", TU Darmstadt 2013.

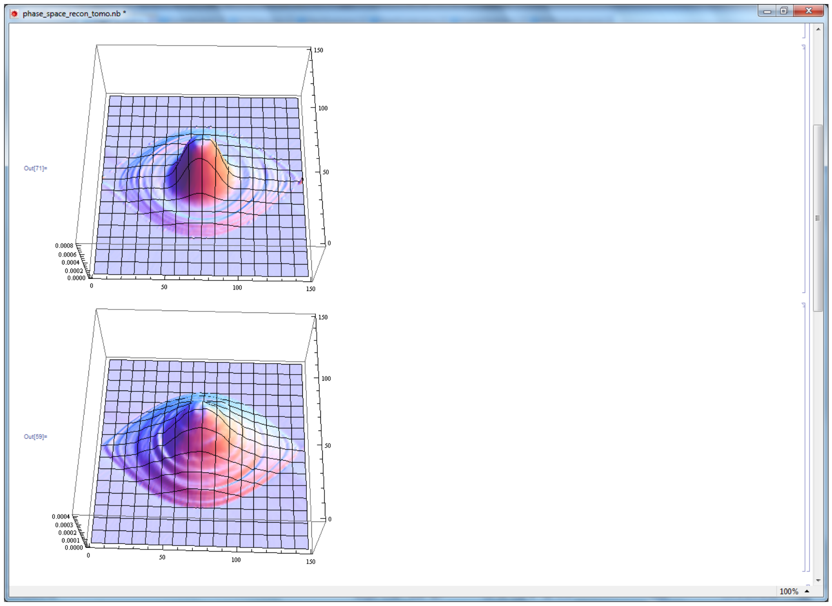


Figure 8: The top figure shows the longitudinal phase space of a bunch 250 ms after injection, which is close to third order resonance $2x + y = 11$. Particles in a certain momentum range periodically cross the resonance due to synchrotron motion and are lost in this time. The bottom figure shows the longitudinal phase space of the same bunch as in Fig. 7, but 250 ms after injection. This working point is away from any transverse resonance.The filamentation has smoothed out due to many synchrotron oscillations. Courtesy : O . Chorniy.

[3] V. Kornilov et al., "Transverse decoherence and coherent spectra in long bunches with space charge", Phys. Rev. ST Accel. Beams 15, 114201 (2012)

[4] G. Franchetti et al., "Recent development in the mitigation of long term high intensity beam loss at FAIR", Proc. of HB 2014 (2014)

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[6] P. Forck, Lecture notes in beam instrumentation, JUAS. (2014)

[7] http://www.qsl.net/va3iul/Noise/Understanding%20Noise%20Figure.pdf

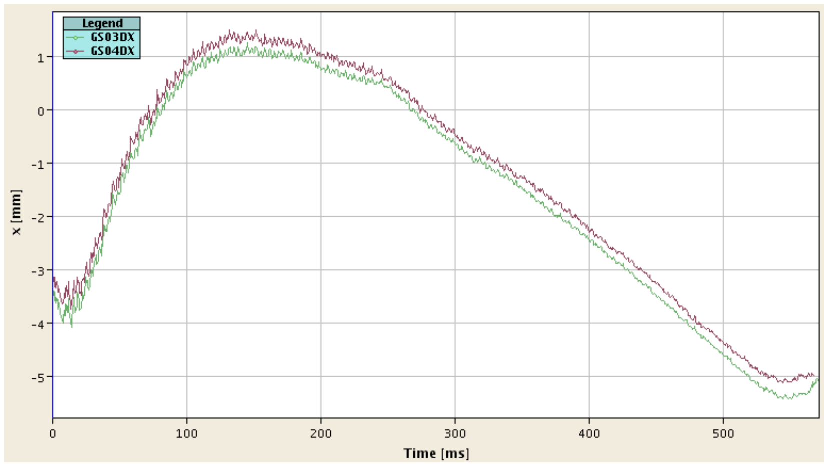

Figure 9: The horizontal beam position from weighted mean after baseline restoration (marked as GS03DX) and regression fit algorithm (marked as GS04DX).

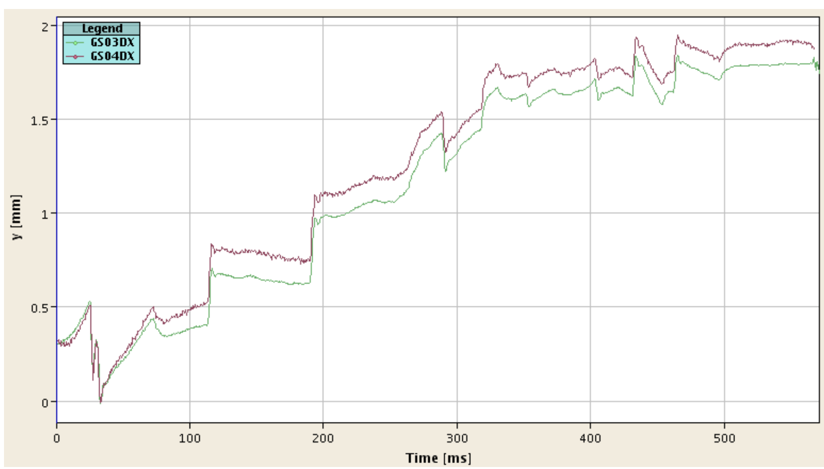

Figure 10: The vertical beam position from Weighted mean with baseline restoration (marked as GS03DX) and regression fit algorithm (marked as GS04DX).