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INTEGRATION OF A PILOT-TONE BASED BPM SYSTEM WITHIN THE GLOBAL ORBIT FEEDBACK ENVIRONMENT OF ELETTRA

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Abstract

In this contribution, we describe the advantages of the pilot tone compensation technique that we implemented in a new BPM prototype for Elettra 2.0. Injecting a fixed reference tone upstream of cables allows for a continuous calibration of the system, compensating the different behaviour of every channel due to thermal drifts, variations of cable properties, mismatches and tolerances of components. The system ran successfully as a drop-in substitute for a Libera Electron not only during various machine shifts, but also during a user dedicated beamtime shift for more than 10 hours, behaving in a transparent way for all the control systems and users. The equivalent RMS noise (at 10 kHz data rate) for the pilot tone position was less than 200 nm on a 19 mm vacuum chamber radius, with a long-term stability better than 1 µm in a 12-hour window. Two main steps led to this important result: firstly, the development of a novel RF front end that adds the pilot tone to the signals originated by the beam, secondly, the realisation of an FPGA-based double digital receiver that demodulates both beam and pilot amplitudes, calculating the compensated X and Y positions.

INTRODUCTION

Like many other lightsources, also Elettra (the Italian synchrotron) is planning its upgrade to Elettra 2.0, a low emittance machine. To obtain the promised figures of merit (high stability, reduced emittance, etc. [1,2]), these new generation machines need several beam diagnostics improvements. In particular, for what concerns electron beam position monitors (eBPMs), the following features are mandatory: nanometer-scale accuracy, long-term stability, reduced current dependence, compensation of different channel behaviours.

Previous experiences in developing analog front end have shown that eBPMs based on pilot tone compensation can fulfil most of these requirements [3,4]. So, we decided to go one step further to demonstrate its usefulness in a real environment, firstly with the realisation of an FPGA-based double digital receiver that demodulates both beam and pilot amplitudes and calculates the compensated beam positions, secondly with the integration of this system in the Elettra Global Orbit Feedback (GOF), replacing a Libera Electron during the normal machine operation.

ELECTRON BPM PROTOTYPE

In order to have maximum flexibility and to compensate the different channel behaviours, including the cables, a modular approach that allows to place the front end in service area is essential. The modules are essentially two, the RF analog front end and the FPGA-based Digital Receiver.

Improved Analog Front End

The front end is similar to the one presented at IBIC 2016 [4], but enhanced and re-engineered in a more compact solution. In the present version the low-noise PLL has been integrated in the box (Fig. 1), together with diagnostic functionalities (voltage and temperature sensors) and complete Ethernet control. Figure 2 illustrates the block diagram of the front end, with the following elements:

1. low-pass filter;
2. high reverse-isolation combiner for the pilot tone;
3. band-pass filter;
4. variable attenuator;
5. low-noise amplifier;
6. splitter;
7. low-noise PLL for the pilot tone generation.

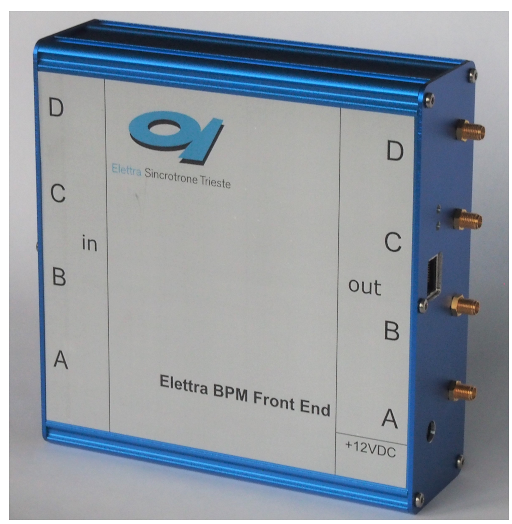

Figure 1: Elettra eBPM analog front end.

FPGA-based Digital Receiver

In the previous publications [4, 5] we described an in-house assembled digitiser (based on Linear Technology LTC2209 ADCs and Altera Stratix III FPGA) developed for first tests of the system, catching only the raw ADC data and transmitted via an Ethernet link thanks to an FPGA. The major limitation of that approach was the off-line processing with the FFT technique. To overcome this issue, the FPGA code has been completely rewritten, implementing a parallel double digital receiver.

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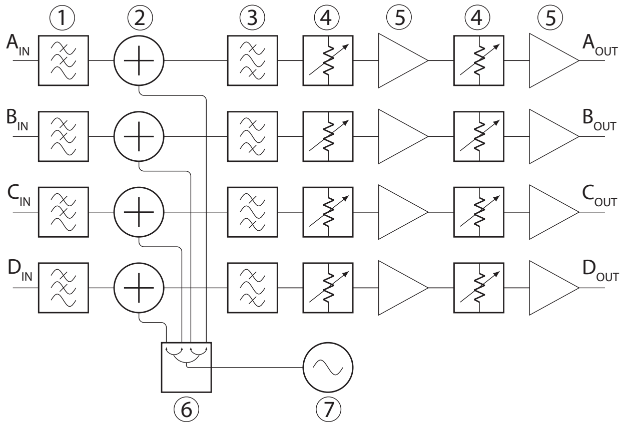

Figure 2: Analog front end block diagram.

The ADC data (running at 150 MHz) are multiplied by sine and cosine generated from a NCO (numerically controlled oscillator) at the undersampled beam RF frequency. The down-converted signals are then decimated using CIC (cascaded integrator-comb) and FIR (finite impulse response) filters at revolution frequency (turn-by-turn, 1.156 MHz).Finally, the amplitudes are demodulated using I and Q data and subsequently decimated again to 10 kHz rate. After this, X and Y position are calculated with the traditional difference-over-sum (DoS) algorithm.

A second NCO, tuned at the pilot frequency, feeds a replicated parallel processing chain that retrieves the pilot positions (Fig. 3). The compensation takes place at 10 kHz

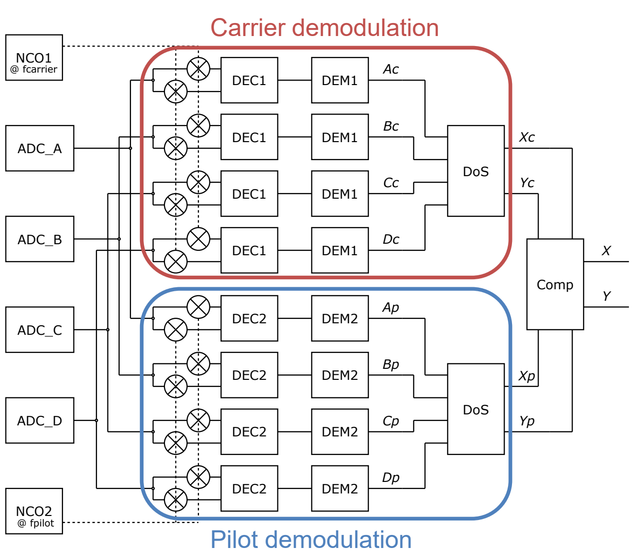

Figure 3: Digital receiver block diagram.

rate, subtracting the pilot coordinates from the beam ones. This is a “non-linear” compensation easier to implement in FPGA (it requires only adders), different from the one used in a previous work [3], that was implemented since it was measured that, in spite of its higher simplicity, returns the same values for small variations, up to 10 mm from the centre.

Three Gigabit Ethernet interfaces on SFP modules are used to control the system and to transmit data to Elettra global orbit feedback. Figure 4 shows the digitiser in Elettra Service Area.

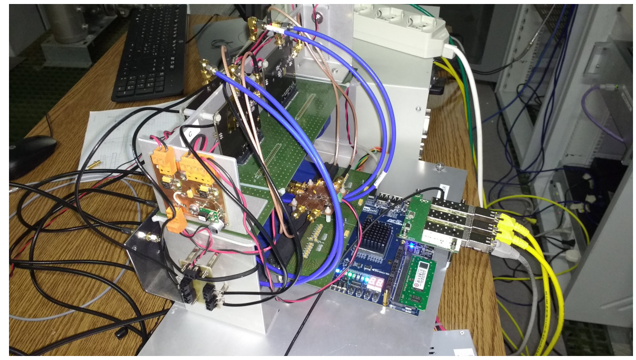

Figure 4: Digitiser in Elettra service area.

CHARACTERIZATION

In order to verify the correct functionality of the system, we decided to emulate a fixed beam at first using a Rohde&Schwarz RF signal generator plus a 4-way splitter, then summing the signals from the beam and dividing them with two back-to-back splitters. Both the approaches gave the same results. The carrier frequency is 499.654 MHz, while the pilot frequency is 501.281 MHz.

Performances

Feeding directly the ADCs inputs without the front end and driving them approximately at 80% of full scale gives an rms noise of about 80 nm on 10 kHz data rate, considering a scale factor of 20 mm. Adding the analog front end, the noise increases up to 180 nm rms, in line with the noise figure of about 6 dB of the front end.

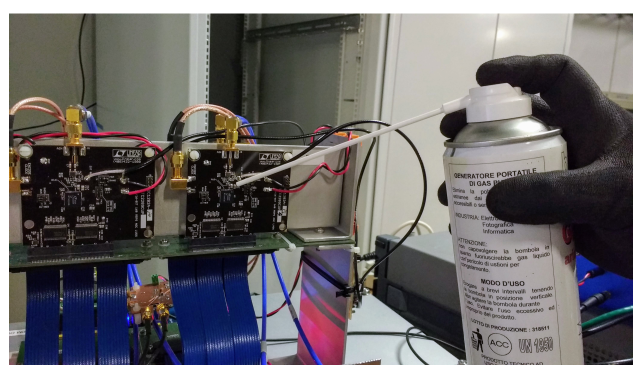

Figure 5: Changing temperature of ADC D.

Temperature Changes and Cables Wobbling

Several test were performed to confirm once again the effectiveness of the compensation. As shown in Fig. 5, the ADC D temperature was lowered by blowing compressed air on the chip. While the resulting drifts for the carrier (beam) and the pilot positions were similar and about 25 µm for both the coordinates (Figures 6 and 7), the compensated ones (Fig. 8) exhibited residual drifts less than 1 µm.

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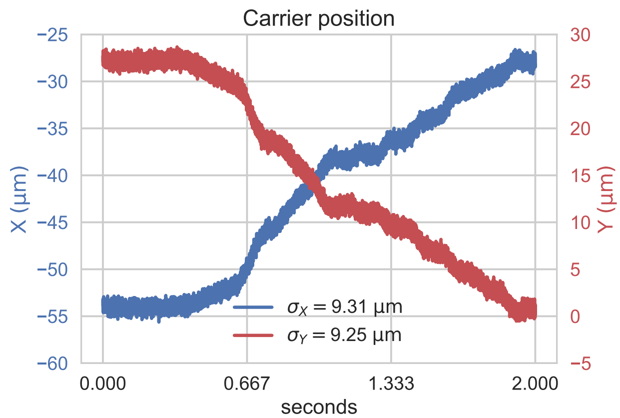

Figure 6: Carrier position during ADC temperature change.

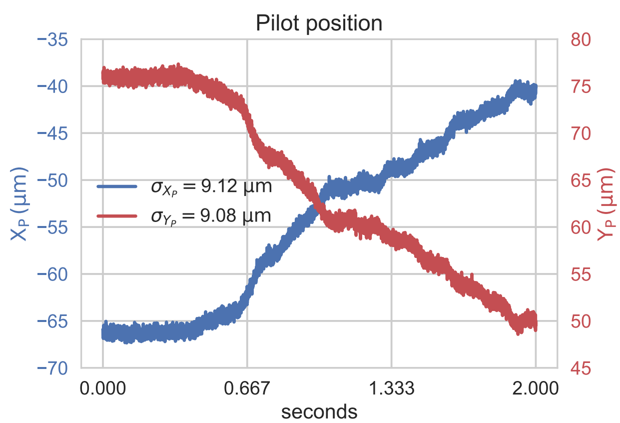

Figure 7: Pilot position during ADC temperature change.

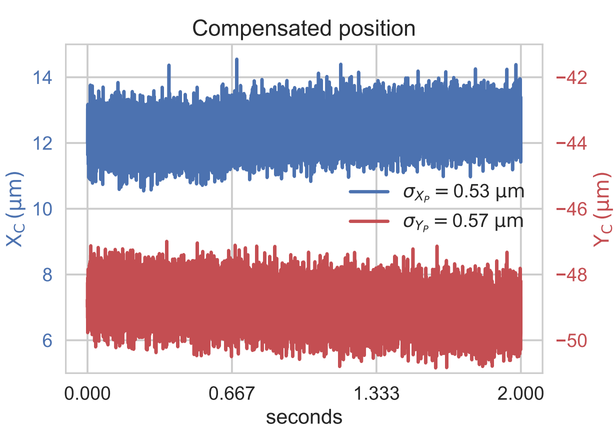

Figure 8: Compensated position during ADC temperature change.

The next step was to bend and wobble a coaxial cable located between the front end and the digitiser. During this operation, the positions oscillated in an interval of about 10 μm, as stated in Fig. 9 for the carrier and in Fig. 10 for the pilot. Also in this case the compensation dramatically reduces the effect, showing residual oscillations less than the peak-to-peak noise (Fig. 11).

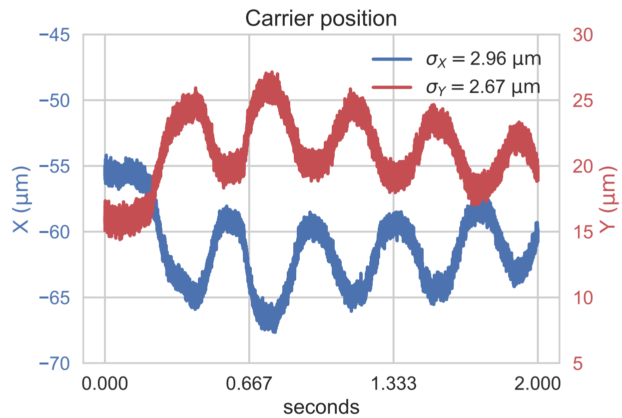

Figure 9: Carrier position during cable wobbling.

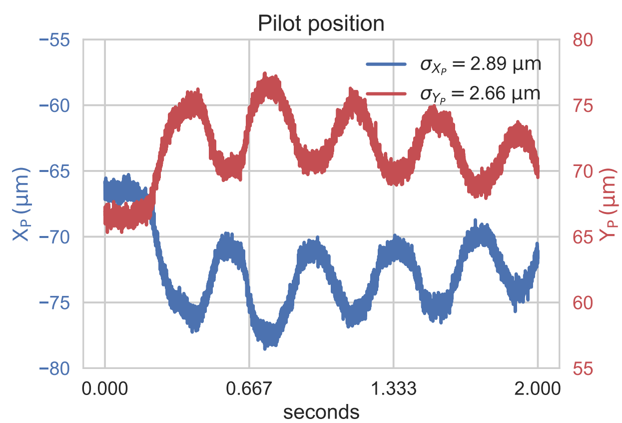

Figure 10: Pilot position during cable wobbling.

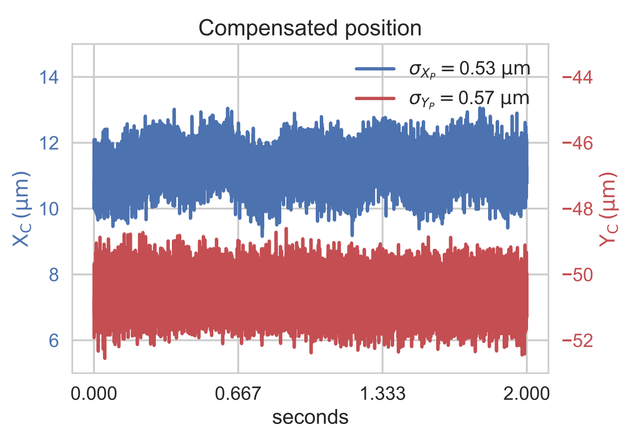

Figure 11: Compensated position during cable wobbling.

Spectral Coherence

Intuitively, the compensation is a powerful tool for correcting "slow" mismatches: thermal drifts, cable variations, gain differences. To optimize the system, a good practice should be to limit the bandwidth of the pilot positions. This would allow to reduce the high frequency content that does not have meaningful information, reducing further unwanted noise on the compensated positions.

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A way to estimate the frequency range where the effectiveness is maximum is using the spectral coherence $C_{xy}(f)$: it measures the relation between the signals x and y. We recall its definition in the following equation:

$$C_{xy}(f) = \frac{|G_{xy}(f)|^2}{G_{xx}(f)G_{yy}(f)} \tag{1}$$

where $G_{xy}(f)$ is the cross-spectral density between the two signals, and $G_{xx}(f)$ and $G_{yy}(f)$ the power spectral density of x and y respectively. Figure 12 shows the calculated coherence between X of the carrier and X of the carrier ($C_{X_C X_P}(f)$) on the 10 kHz data, taking 100 000 samples (equivalent time of 10 s) and zooming up to 200 Hz. The result indicates that the compensation can be useful up to roughly 100 Hz, with a coherence index of about 0.8. The coherence of Y coordinate ($C_{Y_C Y_P}$) is not shown on the figure for space reasons, but behaves nearly in the same way.

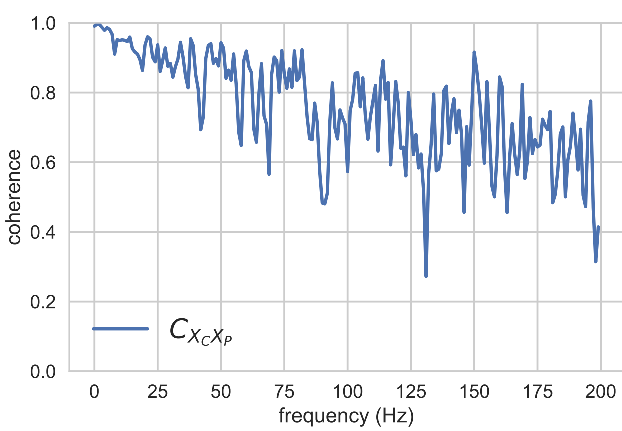

Figure 12: Coherence between X of the carrier and X of the pilot.

RESULTS WITH BEAM

The best way to validate the prototype is to test it in real conditions. So, we replaced an existing Libera Electron BPM in section 7 of Elettra storage ring. The goal was to show that the new system not only provides better performances, but can also replace through and through a commercial eBPM in a transparent way for all the control systems. Figure 13 shows the block diagram of the complete system, and Fig. 14 the setup in Elettra Service Area.

The right operation of the Global Orbit Feedback relies not only on the goodness of the data acquired by the BPMs, but also on their correct synchronisation with respect to the revolution clock (or machine clock, MC). Elettra GOF acquires the whole set of BPM data at about 10 kHz (MC divided by 116) and the maximum time mismatch allowed between two packets in the same collecting point must be less than 20 µs. Each BPM emits an UDP packet on an Ethernet link that contains the X and Y positions together with some extra useful information, such as the demodulated amplitudes of the four electrodes(V_a, V_b, V_c, V_d), the sum of them (S) and the quality factor (Q).

So, the following constraints must be satisfied in order to replace the commercial Libera Electron with the in-house developed BPM:

1. time synchronisation: the UDP packet must be emitted in the same time window of the other BPMs belonging to the same collecting point;
2. the existing packet data format has to be maintained;
3. legacy housekeeping control interface (i.e. Tango server).

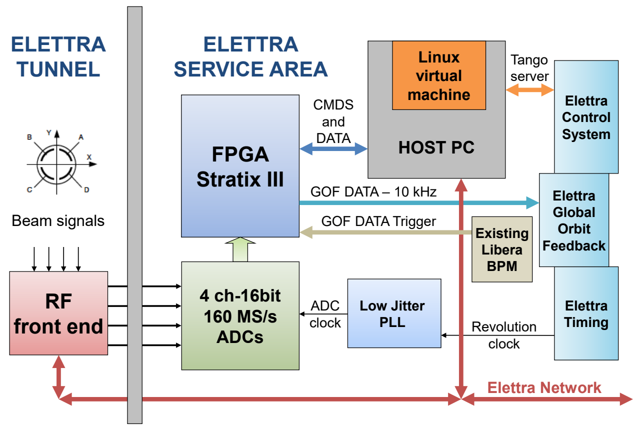

Figure 13: Block diagram of the complete system.

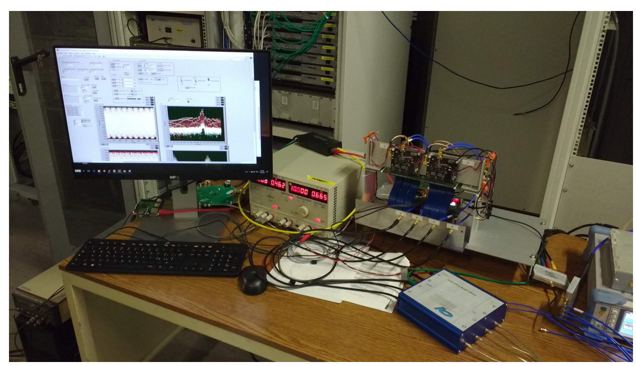

Figure 14: System setup in Elettra Service Area.

Differences with Current Libera System

Our system is phase-locked with the 1.156 MHz machine clock: the generated ADC clock is 150.358 MHz (130 times the MC). All the internal FPGA processing is synchronous and in-phase with the ADC clock and thus with the revolution clock. The processing chain done inside the Libera is different: its clocking system has a FLL (frequency-locked-loop) locked to the MC and the regenerated ADC clock is slightly detuned with respect to the exact MC multiple. This leads to a difference of a 0.02 Hz between the 10 kHz data from the Libera and from our eBPM, resulting in a periodical drop of packets every 50 s, due to the time scrolling of the GOF acceptance window.

This issue was solved by using the replaced Libera: due to the unavailability of trigger outputs on the Libera, we acquire the sent UDP packet via a SFP link with our electronics and use it as a trigger.

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Tango and GOF Integration

The prototype has a basic connectivity on the three Gigabit Ethernet interfaces:

- the first port is reserved to GOF connection: the UDP packets are structured in the same way as the Libera ones, containing the compensated positions;
- the second is dedicated for trigger purposes explained in the previous section;
- the third is used for configuration and on-demand data (NCO tuning, raw ADC buffers, calculated positions of pilot and carrier).

The latter communicates with a Linux virtual machine installed on a host computer. Its task is to analyse the data at 10 kHz and therefore perform additional operations (Fig. 15):

- configure in a proper way the gain of the analog front end (automatic gain control, AGC) and the amplitude of the pilot tone;
- log all the relevant data for diagnostic purposes;
- instance correctly a Tango BPM server for all the control systems outside the GOF, calculating slow data at 10 Hz and less.

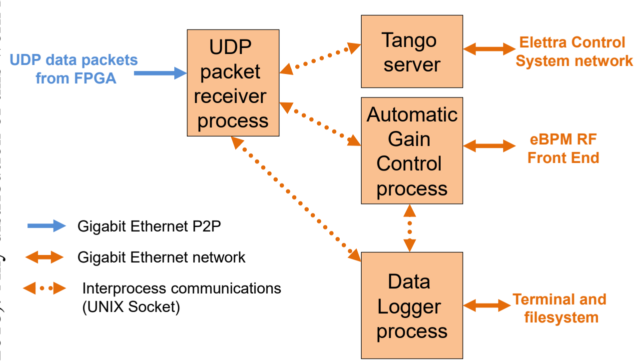

Figure 15: Internal processes of the Linux VM.

Data Obtained During Dedicated and User Shifts

The machine ran successfully with our electronics for more than 24 hours during a dedicated shift. The obtained resolution was about 180 nm, while the long term stability was better than 800 nm in 24 hours, operating at 2.0 GeV and 310 mA, always considering a scale factor of 20 mm and a data rate of 10 kHz. Figure 16 clearly shows the different behaviour on the position caused by real beam movements or attenuation changes/thermal drifts.

The trial was extended in order to include also 10 hours of user shift: during these tests no packet losses, no software or firmware hangs or structural issues have been detected.

Using Pilot as System Diagnostic

The pilot approach has also some not obvious advantage as system diagnostic tool: during the preliminary test an unusual drift on pilot positions was recorded. Looking to the demodulated amplitudes of the four channels, a drop was noticed in channel C. A detailed inspection of the hardware revealed a broken link of the common reference voltage towards ADC C (Fig. 17).

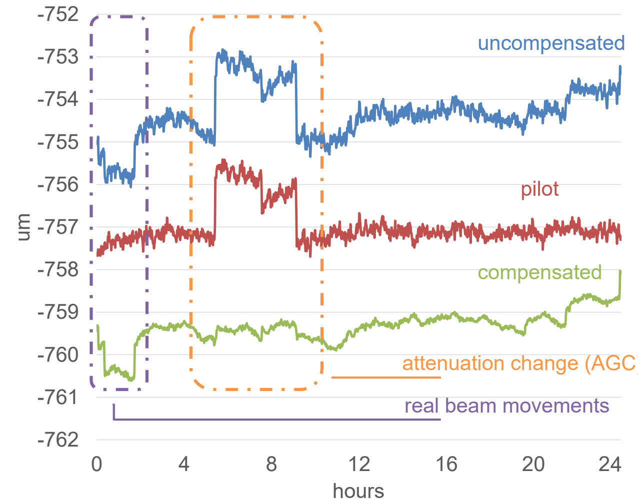

Figure 16: Beam Y-position in a 24-hours time window.

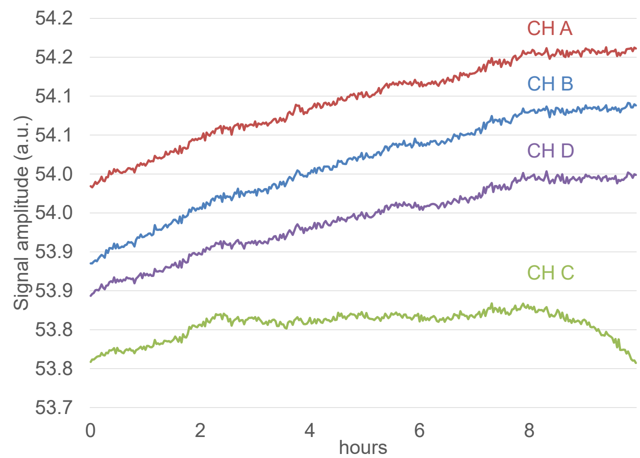

Figure 17: Issue on ADC reference voltage.

Without the pilot information (that should be stable), this kind of malfunction could be detectable only developing an offline dedicated setup, while thanks to the presence of the pilot it is immediately available online.

CONCLUSION

In this paper we presented the successful integration in the Elettra global orbit feedback environment of a modular eBPM prototype based on pilot-tone compensation, consisting in an analog front end and a FPGA-based digitiser capable of parallel demodulation of beam and pilot signals, with resolution and long-term stability both at sub-micron level. The effectiveness of the compensation has been proven during dedicated and user machine shifts: not only as a corrector of thermal drifts, cable variations and gain changes but also as an on-line diagnostic of the system.

When time-domain processing is needed, the system allows to catch the not compensated raw ADC values (e.g. first turn measurements) just turning off the pilot tone, remaining useful for calibration purposes to be done just before the measurement or between bunches. In fact it has to be reminded that all BPM systems based on decimation process

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treat data in frequency domain, which means that a stable machine with a stored beam, or, at least, capable to accumulate a sufficient number of turns to have significant data at 10 kHz is required.

Finally, research on further upgrade of the system is still ongoing about many crucial points: hardware changes will be evaluated, considering various bandpass filters, newer ADCs and so on, and taking in account different scenarios, like first turn, turn-by-turn and tune measurements.

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