A Novel Electron-BPM Front End With Sub-Micron Resolution Based on Pilot-Tone Compensation: Test Results With Beam

G. Brajnik, S. Carrato (Università degli Studi di Trieste, Trieste, Italy)

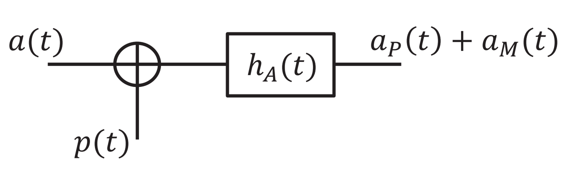
S. Bassanese, G. Cautero, R. De Monte (Elettra-Sincrotrone Trieste S.C.p.A., Trieste, Italy)

Beam Position Monitors measure the position of the particle beam, allowing the orbit correction system to stabilize it. Typically, the position is obtained by using a difference-over-sum (DoS) algorithm involving the signals coming from four transducers. At Elettra, an internal project has been started to develop an eBPM capable of achieving sub-micron resolution with a self-compensation feature.

Accuracy in BPM systems is strongly influenced by the following factors: beam current dependency, thermal drifts of electronics (filters, amplifiers, ADCs) and variations of the frequency response of the cables due to changes in temperature or humidity. All of these issues are responsible for inter-channel gain differences, which modify the calculated position.

In this work, we demonstrate for the first time the continuous calibration of the system by using a pilot tone for both beam current dependency and thermal drift compensation, eliminating the need for thermoregulation. To achieve these results, we developed a new RF front end that combines the four pick-up signals originated by the beam with a stable and programmable tone, generated within the readout system.

Proposed compensation

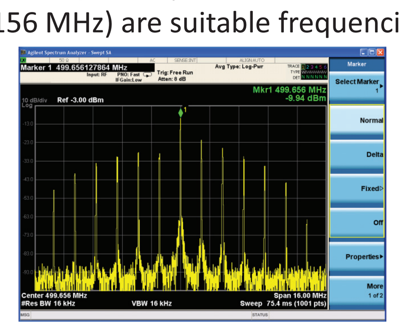


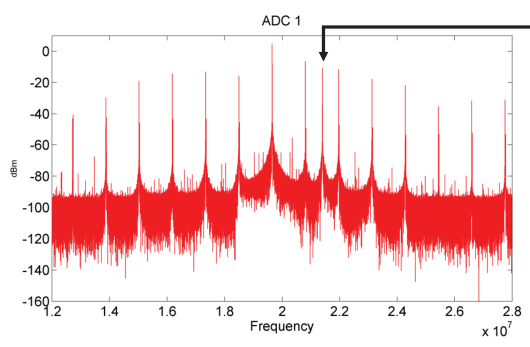
$$A_P(f) = H_A(f) \cdot P(f)$$
$$A_M(f) = H_A(f) \cdot A(f)$$
$$A(f) = \frac{A_M(f)}{A_P(f)} \cdot P(f)$$

$$x = L \cdot \frac{{a_M}/{a_P} - {b_M}/{b_P} - {c_M}/{c_P} + {d_M}/{d_P}}{{a_M}/{a_P} + {b_M}/{b_P} + {c_M}/{c_P} + {d_M}/{d_P}}$$

The DoS algorithm is sensitive to inter-channel gain differences, in particular if these are time-variant. The proposed compensation adds a fixed sinusoidal tone (same for all the channels) to the original signal. In order to achieve an effective correction, the pilot-tone frequency has to fall near the carrier one, without interfering with the latter. The equations above show the model used: $a(t)$ is the input signal, $p(t)$ the reference tone, $h(t)$ the response of the channel (the Fourier transforms are in upper case). The position of the tone is crucial: only the gaps between the harmonics (spaced by the revolution frequency, 1.156 MHz) are suitable frequencies.

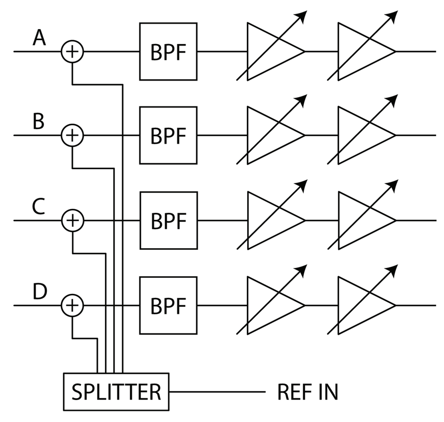
Spectrum of the signal coming directly from the electrodes

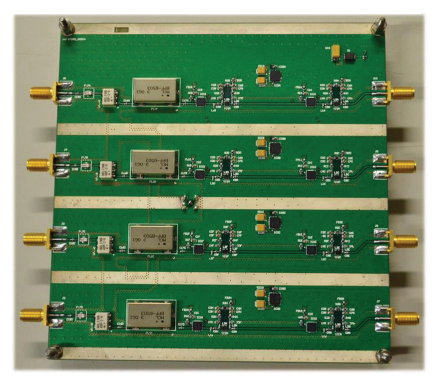




FFT of the signal acquired through the entire system: notice the introduction of the pilot tone

Analog RF front end



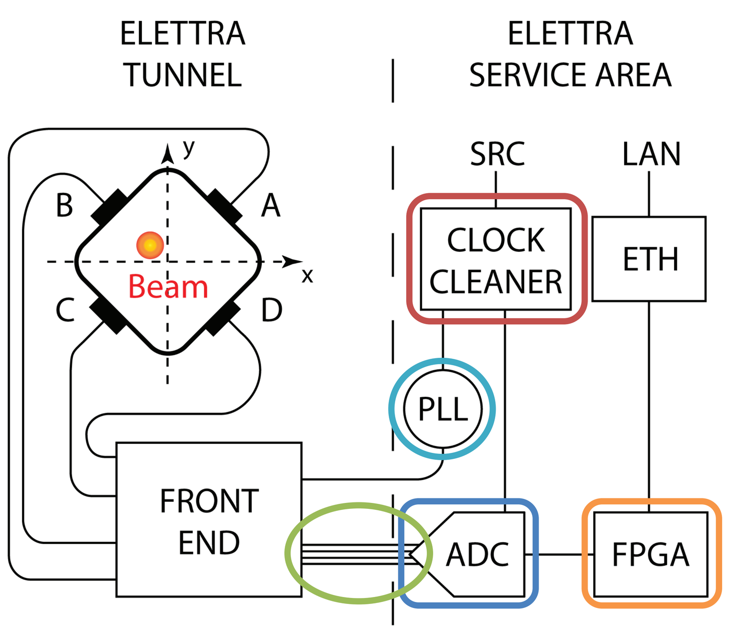


Figures on the left show the block diagram of the system and the manufactured board:

- the pilot tone is split into four paths by a high-reverse-isolation splitter that guarantees more than 52 dB of separation between the outputs;
- a coupler sums the tone with the signal from the pick-ups, adding further 25 dB of isolation to prevent inter-channel crosstalk from the path of the pilot tone;
- all the signals pass through a bandpass filter, centered at 500 MHz with a bandwidth of 15 MHz, and two variable-gain stages, composed of low-noise, high-linearity amplifiers (G=22 dB, F=0.5 dB, OIP3=+37 dBm, P1db=+22 dBm) and digitally controlled attenuators (7 bits, up to 31.75 dB of attenuation, steps of 0.25 dB).

It has to be noted that being the front end a separate unit, it can be placed as near as possible to the pick-ups, with two main advantages: better signal-to-noise ratio and the possibility to compensate the cables.

Measurement setup



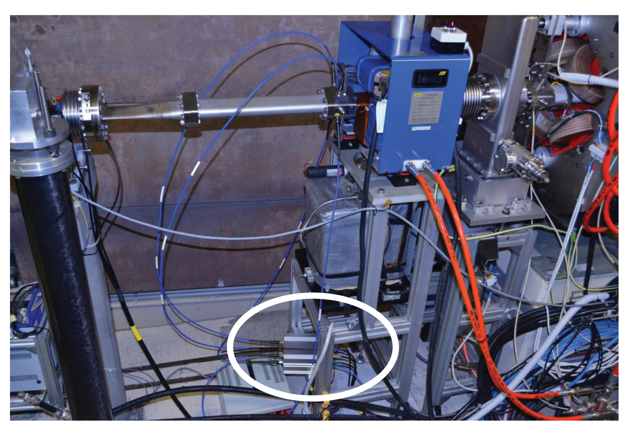
Clock conditioner locked to Elettra storage ring clock

Ultra-low-phase-noise PLL for reference tone generation

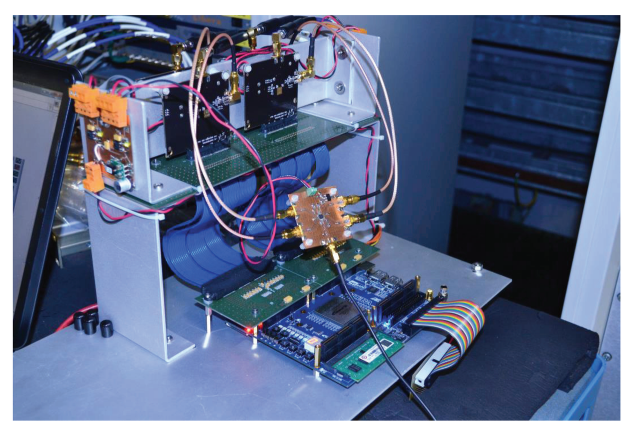
Digital board with FPGA, DDR2 RAM and ethernet link

160 MS/s, 16 bit ADCs

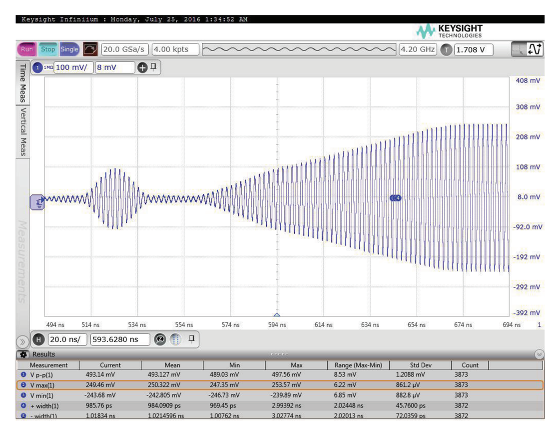
20-metre long cables



The RF front end has been placed in Elettra tunnel area and connected to a button BPM of the storage ring (chamber average radius ~19 mm). The in-house assembled digitizer is located in the service area.



The raw data stream from the digitizer is transmitted via an Ethernet link. The position is calculated offline, where the FFT of each channel provides the amplitude of the carrier and the pilot.



A single bunch has been injected to obtain a hybrid filling pattern. The figure above shows the front-end output: the filter impulse response can be clearly seen.

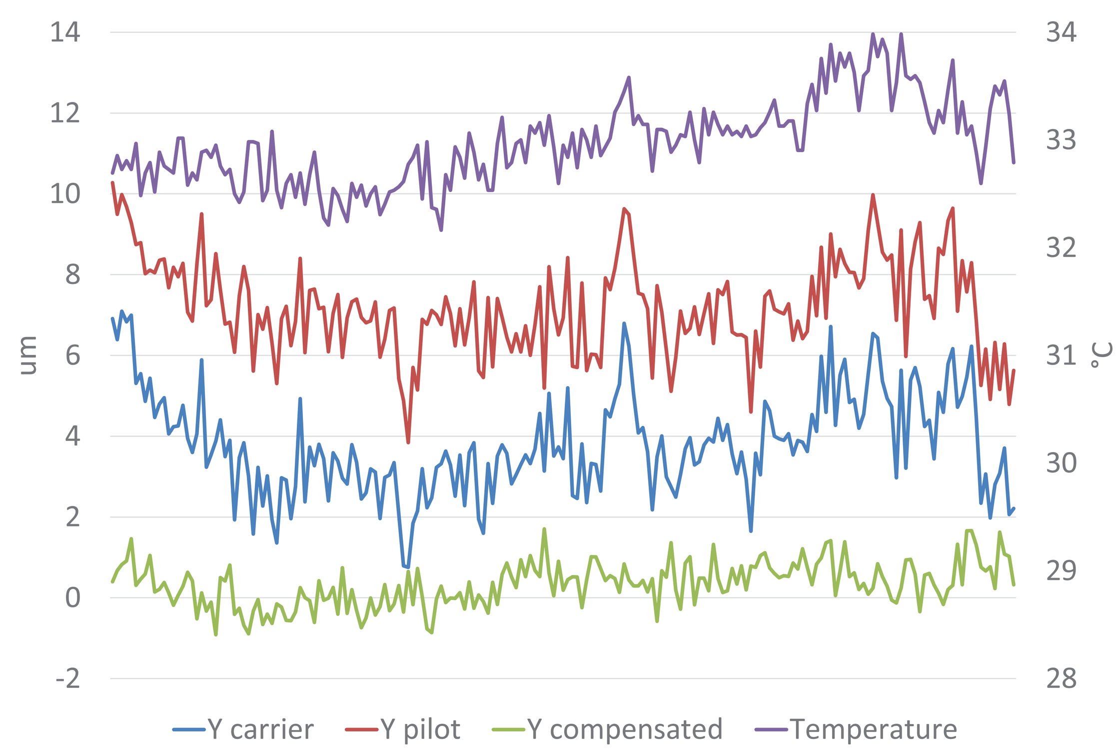
Results

The following results have been collected with Elettra storage ring running in normal operation, 2.0 GeV and 310 mA. The BPM pick-ups used are close to an insertion device and between two bellows. The bellows assure the mechanical decoupling from the rest of the machine. The beam orbit is kept stable at the center position by the global feedback.

- The 499.654 MHz carrier and the 504.6 MHz pilot tone are undersampled respectively at 19.654 MHz and 24.6 MHz.
- The input signal coming from the beam is about -6 dBm with 310 mA of current.
- Carrier and pilot amplitudes measured at the ADCs input are both 0 dBm, for a total amplitude of +6 dBm, that corresponds at the 80% of the ADCs working range.

- Using the pilot as a stable reference, the resolution with an FFT of 2.4 MS and a chamber radius of 19 mm is about 150 nm.
- Influence of the pilot on the calculated position: no changes have been seen switching on and off the tone.
- Deliberate beam movements have been performed, with steps of 1 µm and 10 µm: the compensation can improve the measure up to 2.5 µm.

Changes in temperature and positions



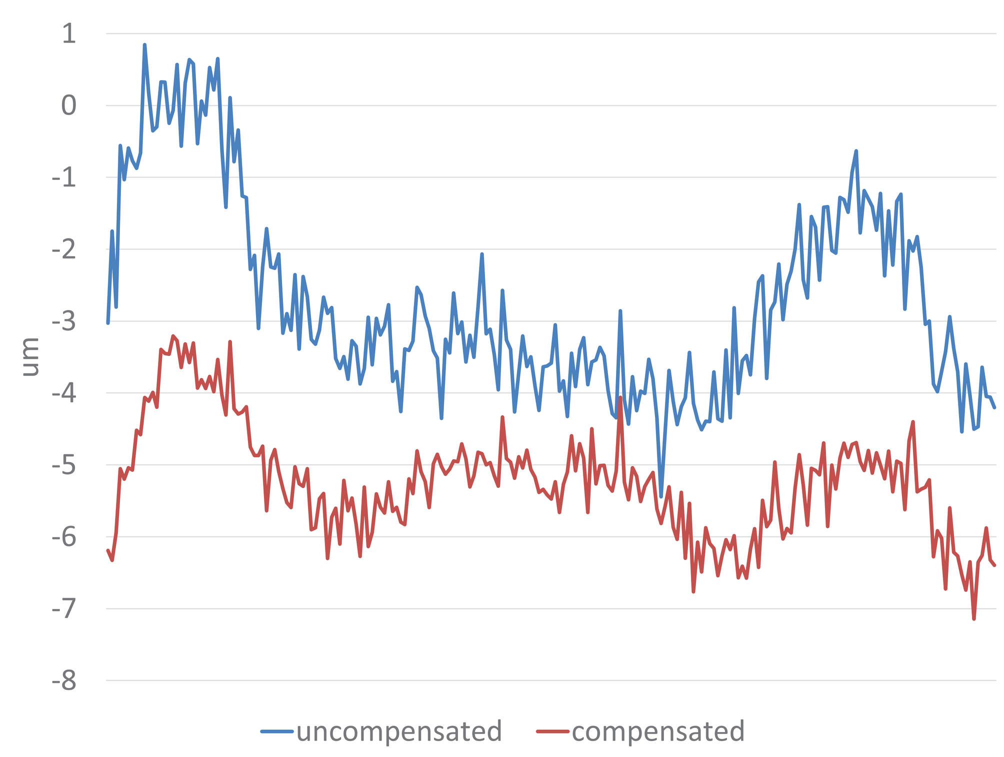
The figure on the left shows dependence of the amplitude of the signals on the temperature of the ADCs (measured with sensors).

- A real signal from the beam emulates a centered and stable beam (using a splitter).
- Identical thermal drifts affect the carrier and the pilot.
- The compensation improves the standard deviation of the position from 1.26 µm to 0.54 µm in a time window of 24 hours.

The figure on the right shows how compensation can be useful for long-term stability.

- The correction reduces the standard deviation by a factor of two, from 1.36 µm to 0.76 µm.
- The average considered radius of the chamber is always 19 mm.
- The position is calculated on real signals from the beam, without using a splitter.

Beam Y-position in a 24-hours time window



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FUTURE WORK

- Implementation of the position calculation in FPGA with digital receivers
- Optimization of the characteristics of the pilot tone (amplitude, frequency) in relation to the compensation
- Development of a FMC digitizer board with new 16-bit, 210 MS/s ADCs
- Hardware improvement in the front end: evaluating various filters for single pass machines