BEAM PHASE MONITOR USING A SINGLE LIBERA BRILLANCE

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Abstract

At the ESRF we now use a single unit of a commercial BPM electronic to measure the phase relation between the stored beam in the storage ring and the beam accelerated in the booster synchrotron. The precise measurement of the relative phase relation with these digital electronic is easy and straightforward due to the availability of the in-phase and quadrature components (I/Q) on each of the four RF input channels at different output rates.

The I/Q demodulation used in the BPM electronics is a widely used RF signal processing technique that is here implemented fully digitally and thereby offers inherent and significant performance improvements over the conventional analogue technique [1].

The phase information between the four input signals can be retrieved after some calculations on the I/Q values.

HARDWARE AND PRINCIPLE OF PHASE MEASUREMENT

The RF signals from the storage ring (SR) come from two BPM buttons. For the booster (SY), two outputs of a ¼ wavelength stripline are available. These latter yield RF signals comparable to the SR-BPM signals in spite of the much weaker booster current. While the SR signal is quasi-permanent and stable, the SY signal only lasts during the 50ms of its acceleration from 200MeV to 6GeV. The booster operates at 1Hz for the so-called long-pulse filling modes (all 352 bunches filled) or at 10Hz for the short-pulse filling modes (single bunch).

At the ESRF the electronic of the BPM system is the commercial *Libera Brilliance* [2]. The Libera provides four channels for RF input signals that, after some analogue amplification, are digitized at a rate of 304 times the orbit frequency (355kHz). The ADC sampling rate is therefore close to 108MHz.

To measure the phase between the two sources one signal of each (SR and SY) would be sufficient. Nevertheless, treating simultaneously two signals of each source (thus using the four input channels) allows performing intrinsic shot-to-shot cross verifications on resolution and reproducibility (see more detailed explanations below).

An identical system has now been added for phase measurements between the storage ring beam and the RF cavity signals. The two units do not apply the so-called RF-crossbar-multiplexing calibration (essential for stable BPM measurements), nor any digital signal conditioning for amplitude and phase compensations. So each unit operates simply as a four-channel digitizer for RF signals of 352.2MHz.

Retrieving the phase values

This new Libera-based phase monitor is operated with Matlab routines that read the I/Q data from a Tango device server. From the I and Q values, the complex I/Q data and therefore the angles are calculated. 2π phase jumps are smoothed and 2π integers removed so that the phase value is always expressed in a value between 0 and 360º.

The relative phase is not affected by the pseudo PLL

Since the numeric oscillator of the Libera is phase locked to the orbit frequency through an external clock input, and the ADC sampling clock is generated by the 304 multiplication factor, such an RF sampling system is not a true phase locked loop (PLL) system.

This limitation is easily observed when using two Libera units with strictly identical RF input signals and an identical clock input (355kHz), and then observing the fluctuations of the obtained phase information between the two units. However, this phase wobbling due to this pseudo PLL affects the four input signals equally and is therefore fully cancelled out. This is shown in Fig.1 for two RF signals. The data are recorded over nearly two seconds at 5.5kHz.

The upper-left diagram shows huge fluctuations of the I/Q values. On the other hand the stability of the two RF signals (absolute of I/Q) is very high as shown in the upper-right diagram. Calculated angles on the I/Q values of these two RF signals show a huge drift (~7 rad!), in the lower-left plot. But the difference between these, now in degrees in the lower-right plot, shows a precise and stable differential phase measurement with an rms of $5.5\cdot 10^{-3}$ degrees.

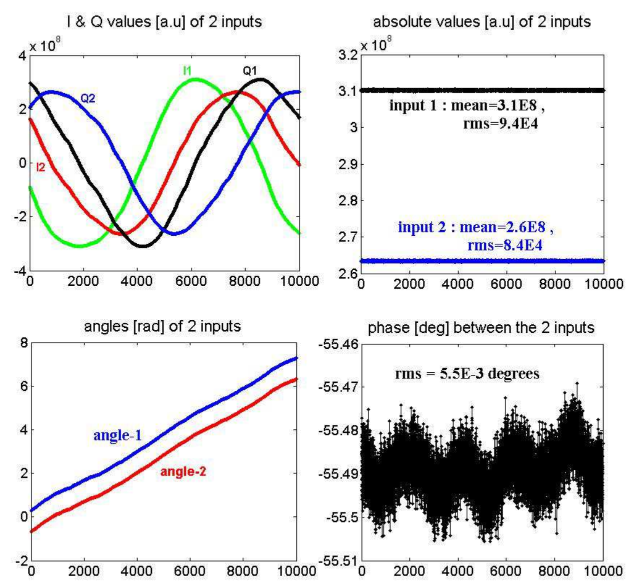

Figure 1: The I/Q values of two identical RF signals in a single Libera unit (upper-left) and the final differential phase values (lower-right), over a ~2s recording at 5.5kHz.

Duplicating the RF signals for systematic and continuous reproducibility checks

For our application we need to measure the phase relation between only two signals: the booster beam and the storage ring beam. Since a Libera unit treats four RF signals, we exploited this to duplicate the two signals to be measured, and then to measure the phase stability between these duplicated signals. The phase calculation being done continuously on all of the four channels means that the differential phase between two duplicated channels yields a verification value of the stability and the reproducibility of the phase information. Fig.2 illustrates the hardware set-up and shows that the duplication is obtained by simply taking and transporting two signals from the same devices (BPM buttons or striplines).

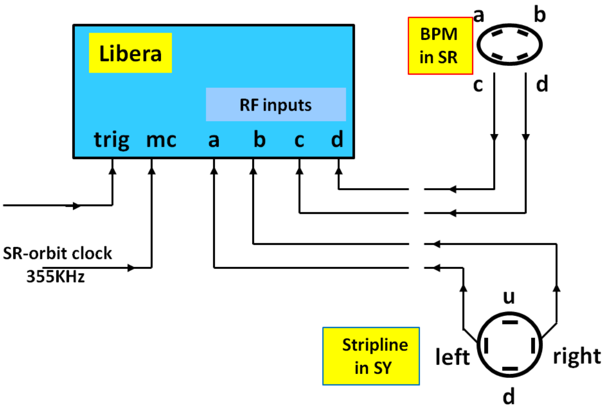

Figure 2: The hardware and interconnections of the phase measurement system between the storage ring (SR) and the booster synchrotron (SY).

RESULTS

The SY beam phase is expressed with respect to the SR beam phase. This means that the phase measurement is only possible with beam current stored in the SR. However, only a few mA are sufficient. The Libera provides data output buffers at 355kHz (DD) and 5.5kHz (DD-64 decimated). These buffers are triggered synchronously with the injection into the booster. For the fastest rate (355kHz) the coverage of the full 50ms from injection to extraction takes ~18000 samples. The Tango device-server cannot handle the read-out of such large buffers at a rate of 10Hz. So, in practice, the system is triggered at a sub harmonic of the injection frequency, typically 1Hz or 0.5Hz.

The results of the SY beam phase behaviour with respect to the SR phase during its acceleration cycle are shown in Fig.3 with the fastest output rate of 355kHz. These measurements were done with 5 single bunches in the SY and 16 single bunches in the SR. The four graphs show the data of a single injection.

A global phase evolution of about 45º can be observed between the injection and the extraction (upper-left graph). The graphs on the right show time details during this injection phase: next to the 13kHz synchrotron oscillations a sawtooth oscillation at 1.1kHz with 10º amplitude is also visible. This is attributed to the phase-loop feedback in the booster RF cavity control system.

In the lower-left graph the intrinsic reproducibility check via the phase stability measurement of the duplicated inputs shows rms values of $21\cdot10^{-3}$ and $97\cdot10^{-3}$ degrees on the SR and SY signals respectively.

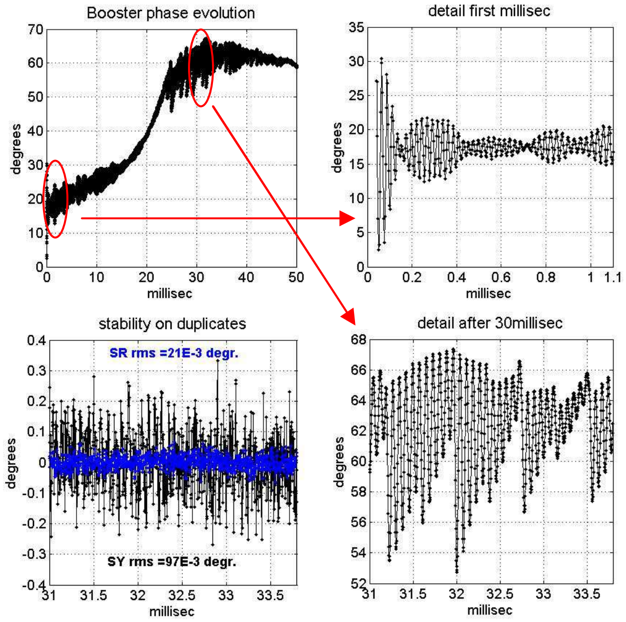

Figure 3: Phase evolution and phase oscillations of the booster beam during its 50ms acceleration cycle.

Similar SY phase measurements, now done at the slower rate of 5.5kHz, are displayed in Fig.4. Fig.4a is an image showing the phase evolution in colours for 63 injection shots. Fig.4b shows two plots of respectively the first (black) and the last (red) injection of a refill; a small phase shift of about 2º can be observed.

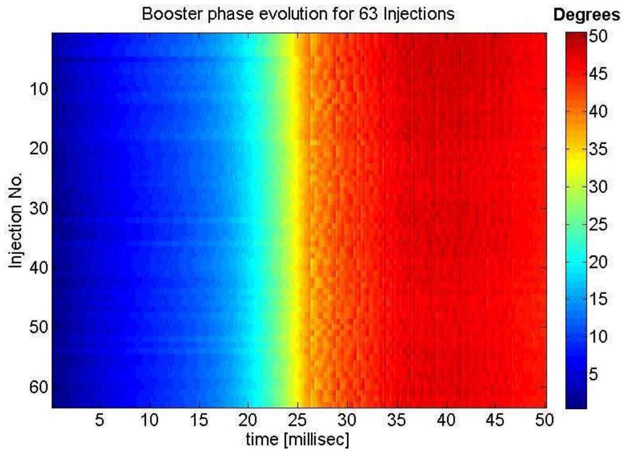

Figure 4a: SY phase evolution during the acceleration cycle for 63 consecutive shots.

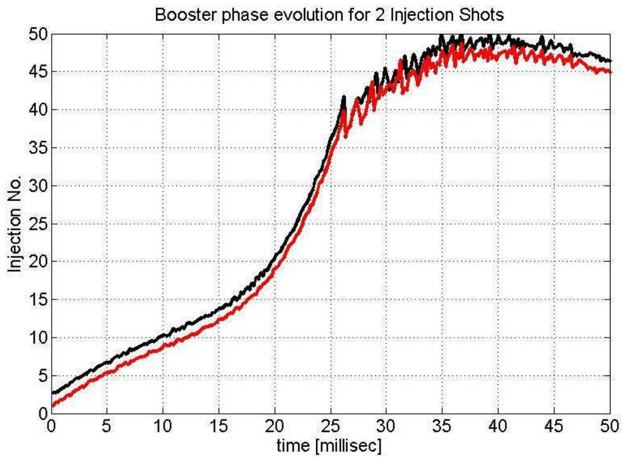

Figure 4b: SY phase evolution during the acceleration cycle between the first (black) and the last (red) injection of a refill.

Performance assessment

This new phase monitor system was tested for short-term fluctuations and noise using an electronic phase shifter on one of the RF inputs. With a pulse generator connected to the control pin of this phase shifter (MiniCircuits JSPHS-446), small phase variations can be introduced at frequencies from DC up to 50kHz and at amplitudes up to 180º. Also the effect of the strength of the RF signals on the noise of the phase measurements was tested.

The results of such tests are shown in Fig.5. The DD output (5.5kHz) is used here and a phase step of 0.48º (100mV on the phase shifter control voltage) is applied on one of the RF inputs at a period of 100ms. The two curves are the results for two different levels of RF input signal strength: the red curve is for a relatively weak RF signal (ADCs filled up to 6% of their 32k full-scale), while the black curve is for an RF signal of 18dB more (50% of 32k full-scale ADC). The rms of the noise at this 5.5kHz output is evaluated to $4.8 \cdot 10^{-3}$ degrees for the weak signal and $2.4 \cdot 10^{-3}$ degrees for the stronger signal. Note that a small phase jump of 0.06º is observed when the RF input signal strength changes by 18dB.

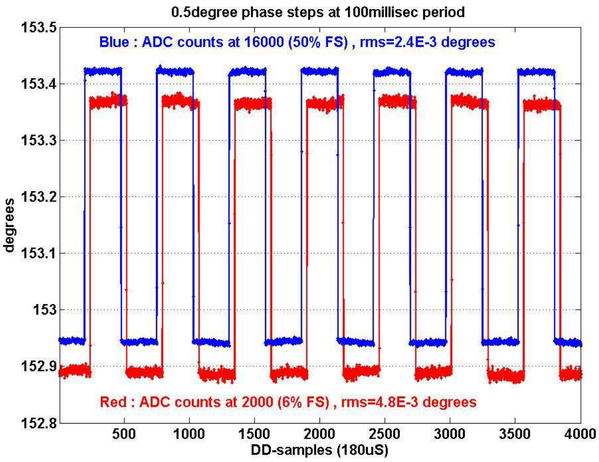

Figure 5: Recordings of phase modulation introduced by an electronic phase shifter.

Drift with temperature

The question of the long-term stability of such SR/SY phase measurement system was raised and in particular the impact of a difference in the cable lengths. These rather long (~30m) cables do not follow identical paths and relative variations, possibly caused by temperature variations, could introduce a phase shift.

First, care had been taken to minimize the difference in length between the cables of one signal (e.g. SR) and the cables of the other signal (e.g. SY). In our case we could limit this to only 6.5m. Furthermore, a test was set up in which such a length of RG214 cable was heated and the resulting phase drift assessed with the system (see Fig.6).

The test showed a phase drift of 1.3º for 12ºC temperature variation, i.e. 0.11º/ºC. For the long-term reliability of the system and the needed precision of the measurement, this value can be considered as negligible.

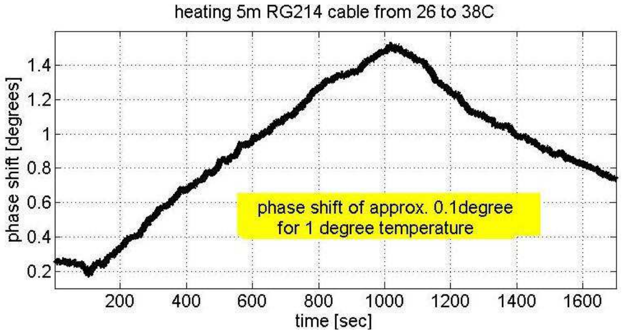

Figure 6: The curve shows a phase drift of 1.3º for a 12ºC temperature variation.

SR / RF phase measurement results

The system used for phase measurements between the storage ring beam and the RF cavity signals (SR/RF) is presently used for slow measurements of any phase drifts or phase evolutions. It measures through the DD buffer at 5.5kHz and then simply averages this data to yield one phase reading averaged in a 1s interval. An example of such recordings is show in Fig.7 for an 8h period. The stability verification value via the duplicated signals is less than $10 \cdot 10^{-3}$ degrees (rms) measured over this 8h period.

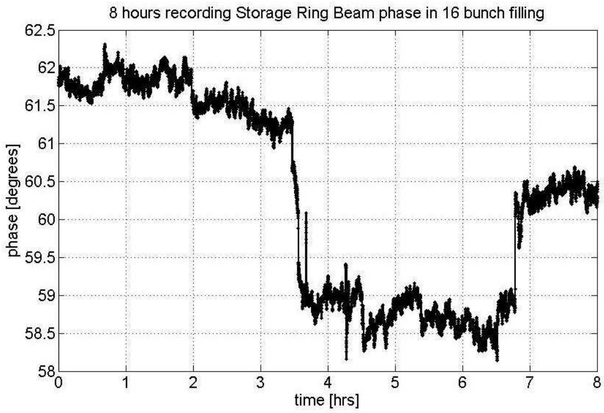

Figure 7: Recordings of the storage ring phase evolution over an 8 hour period (16-bunch filling mode).

ACKNOWLEDGEMENTS

The authors would like to thank F. Epaud and A. Broquet for the device-server development. Thanks are also expressed for the helpful discussions with E. Plouviez, T. Perron and G. Gautier.

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