

UPGRADE OF BEAM PHASE MONITORS FOR THE ESRF INJECTOR AND STORAGE RING

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Abstract

The measurement of the phase relation between the stored beam in the Storage Ring and the beam circulating in the Booster Synchrotron is now done with high precision and at high speed using a single unit of commercial BPM electronics. The quadrature demodulation done in these digital electronics on each of its four RF input channels and the availability of the I/Q components at different output rates make the precise measurement of the relative phase relation, easy and strait forward. The RF signals of the relatively low current Booster come from two stripline outputs while that of the Storage Ring from two small BPM buttons. Treating simultaneously four signals, thus with a redundancy of two to measure the phase between two sources, allows to perform intrinsic shot-to-shot cross verifications on resolution and reproducibility. The long-term stability of this device has also been assessed by verifications against temperature drifts. An identical unit has now been added for phase measurements between the Storage Ring beam and the RF cavity signals.

THE HARDWARE USED AND THE PRINCIPLE OF PHASE MEASUREMENT

The I/Q demodulation is a widely used RF signal processing technique that is nowadays implemented fully digitally and thereby offering inherent and significant performance improvements [1]. At the ESRF the electronics of the BPM system is the commercial Libera Brilliance serving 224 units for orbit measurement and control. [2, 3] These Liberias provide four channels for RF signals that, after some analogue amplification, are digitized at a rate of 304 times the orbit frequency (355KHz) meaning an ADC sampling rate of nearly 108MHz. The RF signal itself at 352.2 MHz means an effective under-sampling system with the RF input signal being mirrored from its 7th Nyquist zone to an intermediate frequency of 28.4MHz. This frequency is being demodulated in a classical I/Q demodulation scheme with a single numeric oscillator providing 2 signals at 90deg phase shift to 2 digital mixers. The resulting I and Q outputs are further decimated in the Digital Down Converter (DDC) to Turn-by-Turn rate (355KHz) and at a 1/64 rate (5548Hz) of that. The phase information between the four input signals can then be retrieved after some further simple calculation on these (four each) I and Q values.

At the ESRF we dedicated 2 spare Libera units to such phase measurements. These 2 units do not apply the so-called RF-crossbar-multiplexing calibration (essential for stable BPM measurements) neither any Digital Signal

Condition for amplitude & phase compensations. So each unit operates simply as a four channel digitizer for RF signals of 352.2MHz.

Relative Phase not Affected by the Pseudo PLL

The numeric oscillator being phase locked to the orbit frequency through an external clock input and the ADC sampling clock being generated by the 304 multiplication factor implies that such an RF sampling system is not a true phase locked loop (PLL) system. This limitation is easily observed when e.g. using two Libera units with strictly identical RF input signals and identical clock input (355KHz) and then observing (the fluctuations of) the obtained phase information between the 2 units.

However, this phase wobbling, due to this pseudo PLL, affects the 4 input signals equally and is fully cancelled out in their relative phase relation. This is shown in Fig.1 for two RF signals into one Libera unit with all 4 graphs recordings over nearly 2sec at 5.5KHz (10Ksamples) : The upper-left shows the I & Q values that show huge fluctuations. The stability of the 2 RF signals (absolute of I and Q) is very high as shown in the upper-right diagram. Calculated angles on the I & Q values of these 2 RF signals show huge drift (~7 rad !) in the lower-left plot. But the difference between these (now in degrees) in the lower-right shows a precise & stable differential phase measurement with an rms of 5.5E-3 degrees.

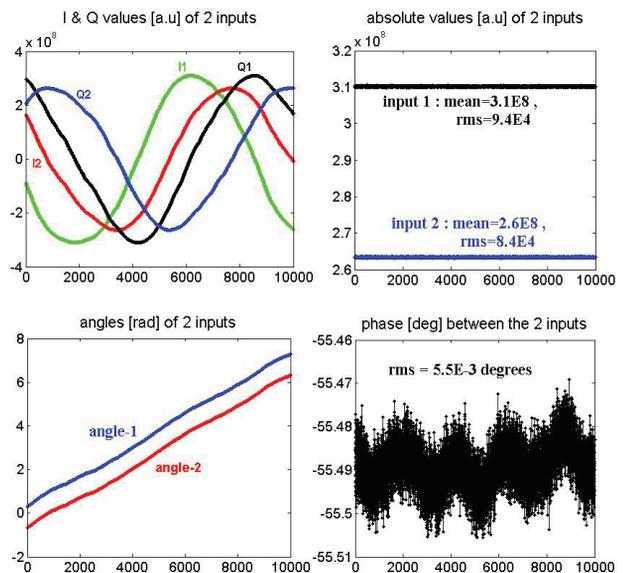


Figure 1: The I and Q values of two RF signals in a single unit (upper-left) and the final differential phase values (lower-right), over a ~2sec recording at 5.5KHz.

Matlab Calculations to Retrieve the Phase Values

At present these new Libera based phase monitors are operated by Matlab routines that themselves read the I and Q data from the device via a Matlab-Tango binding and the existing Tango-device-server. Inside these routines the essential Matlab operations [complex, angle, unwrap and mod] are executed to subsequently put these Is & Qs in complex numbers, to calculate their angles, to correct these angles (i.e. smoothing 2pi phase jumps and removing 2pi integers) so that the phase value is always expressed in a value between 0 and 360degrees.

It is noted here that very similar use of the Libera hardware and its I and Q data, and the above mentioned operations makes it possible to e.g. calculate precisely the cable difference length between the 4 RF cables of a BPM system. [4]

A full application program is in elaboration that should replace these Matlab routines and allow for (a more) user-friendly and non-expert operation and also for systematic storage in the data-base system of the ESRF.

Duplicating the RF Signals for Systematic and Continuous Reproducibility Checks

For our two applications we need to measure the phase relation between only 2 signals per unit : for one system the Booster Beam (SY) versus Storage Ring Beam (SR), and for a 2nd system the Storage Ring beam (SR) versus the RF cavity frequency (RF). Since a single Libera unit treats 4 RF signals we exploited this by duplicating the 2 signals to be measured, and then measuring the phase stability between these duplicated signals.

The phase calculations being done continuously on each 4 channels means that the differential phase between two duplicated channels yields a verification value of the stability and the reproducibility of the phase information that is yielded by the system. The Fig.2 illustrates this hardware set-up for the SY-SR system, and shows that the duplication is obtained by simply taking and transporting 2 signals from 2 buttons (or striplines) of the same devices in the SR and SY Rings. A similar duplication of the signals is also applied for the 2nd system (SR-RF).

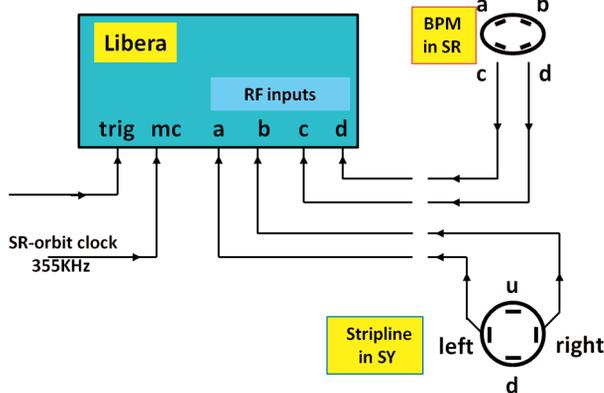


Figure 2: The hardware and interconnections of the phase measurement system between the Storage Ring (SR) and the Booster Synchrotron (SY).

PHASE MONITOR RESULTS FOR BOOSTER VERSUS STORAGE RING

The RF signals from the Storage Ring come from 2 simple BPM buttons while for the Booster 2 outputs of a ¼ wave stripline are available to yield RF signals of comparable amplitude for a (much weaker) Booster current. While the SR signal is quasi permanent & stable, the SY signal only lasts during the 50millisec of its acceleration from 200MeV to 6GeV. The SY operates at 1Hz for so-called long-pulse filling mode (all 352 bunches filled) or at 10Hz for single bunch(es) filling modes.

The SY beam phase is expressed with respect to the SR beam phase in degrees. The minor drawback of this is that SY phase measurements are not possible without a small beam current stored in the SR. However, only a few mA SR current is sufficient. The important advantage is that the long-term stability is better ensured since the cable length differences are very small (<6m) and the paths of these RF cables have a large part (>70%) in common (i.e. side-by-side in same cable trays). This would not be practically possible if e.g. the SY phase was measured with respect to the RF cavity signal.

The Libera provides data outputs (buffers) at 355KHz (DD) and 5.5KHz (DD-64decimated). These buffers are triggered in synchronization with the Injection into the SY. For the fastest rate (355KHz, 2.8us) the coverage of the full 50millisec from injection to extraction takes ~18KSamples. The Tango device-server cannot handle the read-out of such sized buffers at a rate of 10Hz. So in practice the system is triggered at a subharmonic of the Injection frequency, typically 1 or 0.5Hz.

Booster Phase Evolution in its Acceleration Cycle

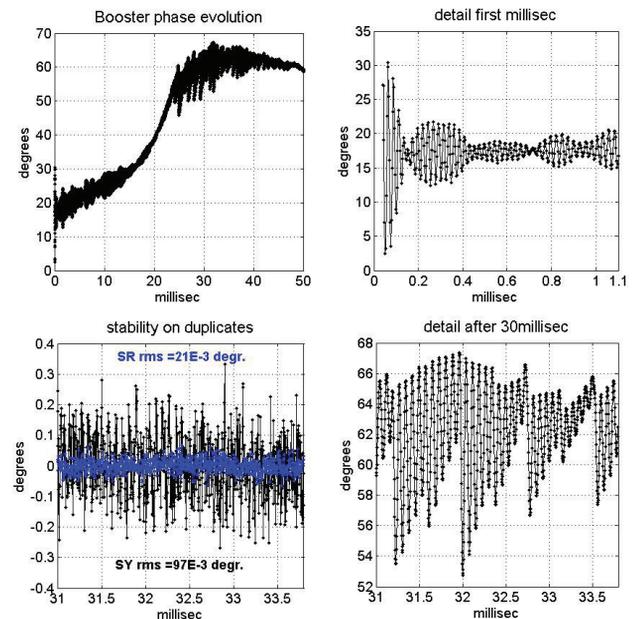


Figure 3: Phase evolution and oscillations of the Booster beam during its 50millisec acceleration cycle.

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The results of the SY beam phase behaviour during its acceleration cycle are shown in Fig.3 with the fastest output rate of 355KHz. These measurements were done under 5-single-bunch mode for the SY and 16-bunch mode for the SR. The 4 sub-graphs show the data of a single injection. A global phase evolution of about 45degrees can be observed between the moments of injection and extraction (upper-left graph). The graphs on the right show time details in this phase record : next to the 13KHz synchrotron oscillations a saw-teeth oscillation at 1.1KHz with 10degrees amplitude is also visible. The latter is attributed to the phase-loop-feedback behaviour in the RF cavity control of this SY RF system.

The intrinsic reproducibility check via the phase stability measurement of the duplicated inputs shows rms values of 21 and 97 E-3 degrees on respectively the SR and SY signals.

Similar SY phase measurements, but now done on the slower rate of 5.5KHz, are displayed in Fig.4a in an image showing phase evolution in colours for 63 injection shots, and in Fig.4b with two plots of respectively the first (black) and the last (red) injection of the re-fill. A small phase shift of about 2 degrees can be observed.

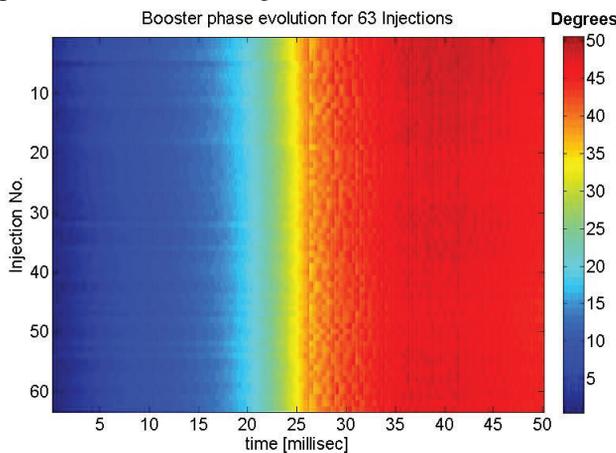


Figure 4a: Phase evolution of the Booster beam during its acceleration cycle for 63 consecutive shots.

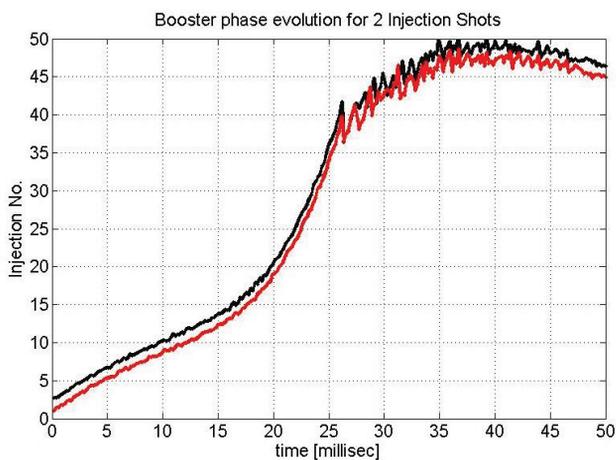


Figure 4b: Phase evolution during the acceleration cycle, for first (black) and last (red) injection of a refill.

PERFORMANCE VERIFICATIONS WITH ELECTRONIC PHASE SHIFTER

This new phase monitor system was assessed on short-term fluctuations and noise in a set-up that uses an electronic phase shifter in 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 upto 50KHz and amplitudes upto 180degrees. Also the effect of the strength of the RF signals on the final noise on the phase results was assessed. The results of one such measurement are shown in Fig.5. The DD (5.5KHz) output is used here and a phase step value of 0.48degrees (100mV at phase-shifter control voltage) is applied at a period of 100millisec. The 2 curves show results for different levels of RF input signal strength : the red curve is for relatively weak RF signals (ADCs filled upto 6% of their (32K) full-scale) while the black curve is for an RF signal of 18dB more (50% of full-scale ADC). The rms of the noise at this 5.5KHz output is evaluated at respect. 4.8E-3 and 2.4E-3 degrees. Note that a small phase jump of 0.06degrees can be observed when the RF input signal strength changes by 18dB.

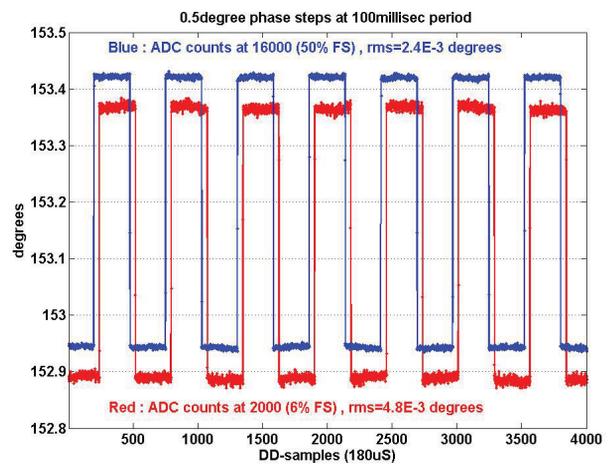


Figure 5: Recordings of phase modulation introduced by an electronically controlled phase shifter.

LONG-TERM STABILITY AND 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 variation of the cable lengths. These rather long (~30m) cables inevitably do not follow identical paths and relative variations, possibly caused by a differential temperature variation, could introduce a phase shift.

Firstly, care had been taken to minimize the length over which the cables from one signal origin (e.g. SR) are different from that of the cables of the other (SY). In our case we could limit this to only 6.5meters. Furthermore a test was set-up in which one such length of (RG214)

cable was being heated and the resulting phase drift assessed with the system (see Fig.6). It showed a phase drift of 1.3degrees for 12C temperature difference, i.e. 0.11degree/C. For the usefulness and reliability of long-term phase measurements this value can be considered as negligible.

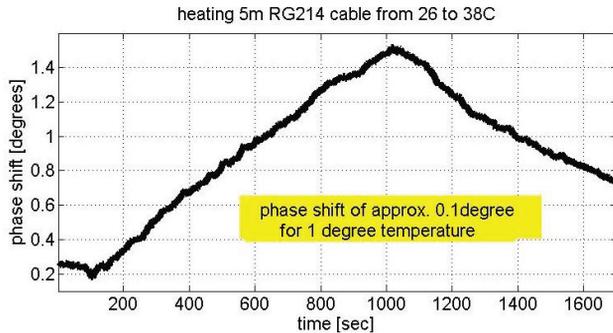


Figure 6: The curve shows the rise and decay of phase shift of 1.3degrees for a 12C differential temperature.

STORAGE RING RESULTS AND FUTURE PROSPECTS OF PHASE MONITORING

The SR-RF system is presently mainly used for slow measurements of any phase drifts or evolutions. It measures through the DD buffer at 5.5KHz and then simply averages this data to yield one phase reading averaged in a 1 sec interval. An example of such recordings is show in Fig.7 for an 8 hour period. The stability verification values via the duplicated signals attained less than 10millidegrees (rms) measured over this same period.

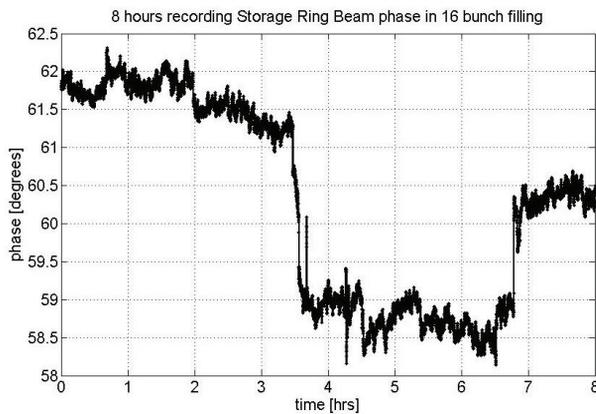


Figure 7: Recordings of Storage Ring phase evolution over an 8 hour period (16 bunch filling).

The same Libera device can also be used with phase measurements on so-called Post-Mortem (PM) buffers. These buffers are triggered by a separate and independent trigger. The interest here is to trigger and save such recordings at the time of an un-expected and un-explained Storage Ring beam dump due to a possibly spurious phase

(glitch) problem in the RF system. This is presently under development with a modification in the device-server to make I and Q values available from the PM buffer readings.

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