FIRST RESULTS WITH THE PROTOTYPES OF NEW BPM ELECTRONICS FOR THE BOOSTER OF THE ESRF

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Abstract

The 25 year old BPM electronics of the ESRF's Booster (200MeV to 6GeV, 300m, 75 BPM stations) are in process of replacement with new modern acquisition electronics. The design and development of this acquisition system was done in collaboration with the Instrumentation Technologies company and has resulted in a commercial product under the name Libera-Spark. It contains RF filtering & amplification electronics in front of 14 bit & 125MHz ADCs for 4 channels, followed by a (Xilinx ZYNQ) System_on_Chip for all processing, that also includes the possibility of single bunch filtering directly on the ADC data. It is housed in a compact and robust module that is fully powered over the Ethernet connection and which facilitates its installation close to the BPM stations thereby avoiding long RF cabling. For simplicity and cost economic reasons this Spark is without PLL and adjustable RF attenuators since not needed for Booster BPM applications, but possible in elaborated versions for other applications. Two prototypes were fully tested with beam and the results in terms of resolution & stability were assessed since delivery in January.

THE ESRF BOOSTER RING AND MOTIVATION FOR NEW BPM SYSTEM

The European Synchrotron Radiation Facility operates a 200 MeV linear Pre-Injector and a full energy fast cycling Booster synchrotron that accelerates the electron beam to the 6GeV energy in an acceleration period of 50millisec before extraction to the 2nd transferline and subsequent injection into the Storage Ring. This Booster presently still uses the original power supplies for the magnets that function with a resonant "white-circuit" at 10Hz cycling frequency, producing biased sine wave currents in these magnets. That magnet's power supply system will be replaced in 2015 by ramping power converters, with a minimum cycling rate of 250ms (150ms ramping up and 100ms ramping down), followed by a partial re-commissioning of the Booster.

The Booster has a circumference of 300m and contains 75 BPM blocks with each 4 buttons of 10mm diameter in a circular chamber of 60mm internal diameter. The 4 buttons are angularly distributed with 4 equal 90deg angle shifts between them, but with a 45deg angle offset with respect to horizontal and vertical planes. The so-called K factor for this BPM geometry is 21.5mm when using the simple delta/sum algorithm for calculating the beam position from the 4 RF signal strengths measured at the buttons.

The RF signal amplitude, at the sma connector of the button feedthrough, is about 300uV rms for 1mA of Booster current. The RF frequency is 352.2MHz and the maximum nominal current 5mA in so-called long-pulse (from Linac) which produces a bunch-train of 352 bunches. However, the Booster also operates routinely in multi-single bunch configurations with only 1 to 5 bunches and typical currents between 0.1 and 0.5mA.

Motivation for the New BPM Electronics with Improved Functionality and Performance

The old electronics and acquisition system had no functionality for Turn-by-Turn measurements and could only perform 6 punctual measurements in the 50millisec acceleration cycle. These old electronics have an RF multiplexer in close vicinity to the BPM block (hence inside the Booster Tunnel) and the rest of the electronics in permanently accessible cabinets, but at RF cable lengths varying between 20 and 60meters. [1]

A few years ago 2 Libera-Brilliance units were installed to perform the signal acquisition of the RF signals from 2 BPM blocks and had been helpful to demonstrate the benefits of more performing BPM measurements, notably serving as a new Booster tune measurement system. However, the Libera system is specifically designed for Storage Ring BPM requirements with incorporated functionalities that have strictly no application in a Booster BPM system with only a beam duration of a fraction of a second.

The search for an alternative, but also more cost-effective, system for the acquisition of the 4 weak RF signals aimed at simplifying the concept to a strict minimum but yet achieving Turn-by-Turn measurement functionality even for (low current) single bunch fillings. A completely new hardware design that needs no maintenance (passive cooling, no disc, power over ethernet) was elaborated by the Instrumentation Technologies company and resulted in a new and now commercial, product, named as Libera Spark [2, 3].

FUNCTIONAL DESCRIPTION OF SPARK

The main features of the Spark device can be resumed as follows :

- 4 channels digitizer for weak RF signals.
- Adequate signal processing for the calculation of the 4 signal strengths, comprising I , Q and Sum values, the beam-position values, and this all for data-rates reduced to Turn-by-Turn rate and lower, and this also optimized for specific (single-bunch) filling patterns
- Efficient and straight-forward interface (SCPI commands) for the control & read-out via Ethernet.
- Suitable and compact chassis & housing, with Power-over-Ethernet (IEEE802.3af standard).

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The Fig.1 shows a block diagram with, on the analogue (left-) side, the four inputs (sma-connectors) followed by RF bandpass filters and RF amplifiers. The total RF gain is such that the subsequent 14bit ADCs reach their full scale (+/-8192 counts) for an RF input level at -40dBm (2.2mV rms). There is no variable RF gain (or attenuation) implemented since for even the highest beam currents in the Booster the ADCs will be below this full range, and this even if the RF cable length between the BPM block and the Spark is only a few meters long (i.e. installation of the Spark inside the Booster tunnel).

The ADCs are running at about 108MHz and so the BPM's RF signal (352.2MHz) is frequency under-sampled inside the 7th Nyquist zone. The exact ADC sample rate should be 108 times per Booster orbit revolution (is 1.000574MHz) but it should be noted that this frequency is determined by a programmable crystal oscillator (XO) which is not locked to any of the real frequencies (RF or Orbit) of the Booster itself. It is therefore up to the user to set (at reboot of the device) the XO such that indeed 108 samples per turn are obtained and further delivered to the Digital Down-Convertor that is realised in the FPGA section and that converts to Turn-by-Turn data rate.

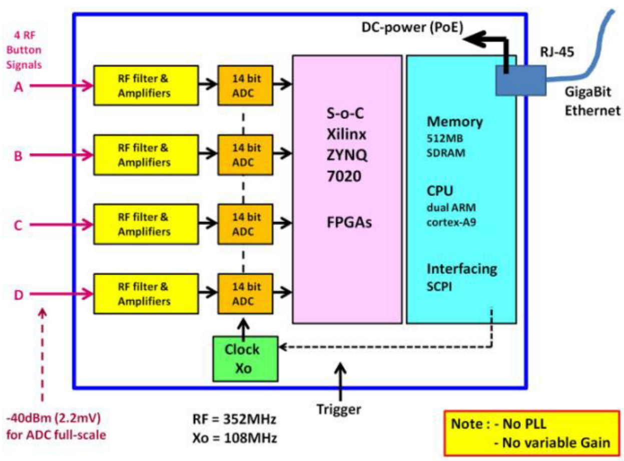

Figure 1: Block diagram of the Spark [um].

The omission of a PLL mechanism (needing itself additional externally provided timing signals) was motivated for both simplification and cost-reduction reasons, and it can be shown (see subsection on synchronisation) that for the short duration of the beam in the Booster (50millisec) such PLL is not needed.

The device can boot via network (using TFTP protocol) or alternatively from a micro-SD memory card (not shown in the above diagram).

SIGNAL PROCESSING THAT COVERS VARIABLE NEEDS AND APPLICATIONS

The Fig.2 shows the scheme of signal processing with the Digital Down Convertor (DDC) that provides a quadrature demodulation on each of the 4 channels, at the XO frequency, producing the I and Q signals at Turn-by-Turn (TBT) rate. This TBT buffer is used to further calculate the absolute signal strengths of the 4 channels and the X and Z position values (using the simple delta/sum formula), taking into account the K factor and possible offsets. A similar, but slower rate buffer is also available at TBT divided by 64.

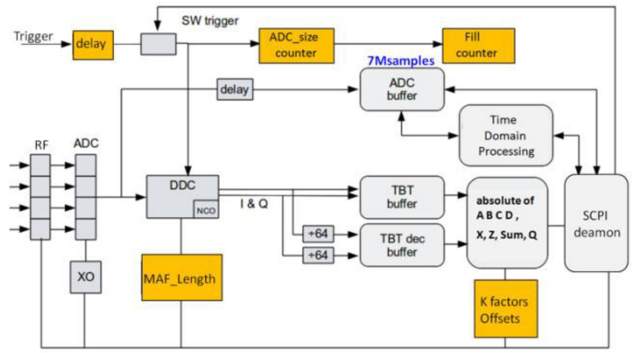

Figure 2: Signal Processing Scheme, the orange blocks indicate input parameters.

The DDC allows applying a pre-filtering on the ADC samples to be used in the subsequent TBT generation of data flow. A parameter called MAF_Length can be set to an integer value below the (ADC_to_TBT) decimation rate of 108. This makes it possible to only select those ADC samples that contain a real RF beam signal as is the case in single-bunch filling patterns. This example is further illustrated in Fig.3 where 432 ADC samples that represent 4 Turns are depicted (in black) together with a possible configuration of that MAF filter in blue. Per orbit turn only the 35 samples defined by the MAF are used in further processing while the other (73) are discarded. It is noted that the ADC buffers (upto 7Msamples each, i.e. representing 65millisec) themselves are available.

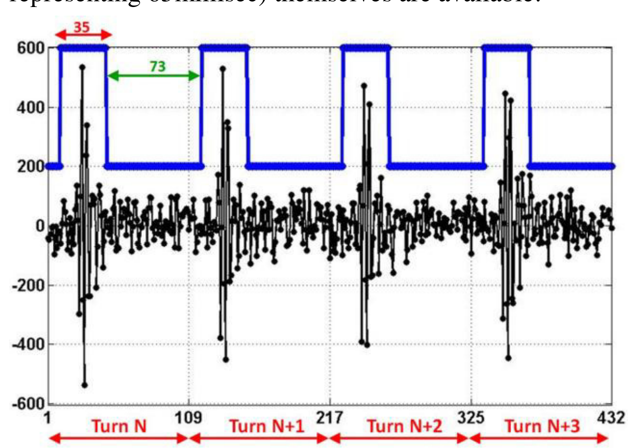

Figure 3: MAF filtering on the digitized RF signal with partial beam fill patterns (in this case single bunch).

Trigger and Synchronisation Issues

The trigger signal plays an important role in the precise timing of T-b-T data, also in the absence of a PLL on the ADC clock. This trigger (after a settable trigger delay) defines the start of the first Turn and also the start of the

MAF filter (if used). It can be shown that if the crystal oscillator is not exactly at 108 times the RF frequency then the MAF window will drift away from its position with respect to the RF beam signal. E.g. at each new trigger the MAF will initially (meaning for the first number of turns) be correctly positioned (as shown in Fig.3), but no longer at much later turn numbers. One should keep in mind here that in a system with 75 BPMs, and each with an individual and free-running crystal oscillator, that such non-rigorous synchronisation between T-b-T data of all stations could limit the usefulness or lead to misinterpretations.

However, the exact frequency values of each Xo in a system with 75 BPMs can be simply determined by an FFT on the retrieved ADC data buffers (of any of the 4 channels) when taken with a circulating beam in the Booster. Any differences of the real Xo frequency with respect to the set-value can then be corrected individually and a next acquisition should confirm then that all Xos are now sufficiently close in real values, and that consequently the T-b-T data of all stations is in phase, even 50millisec after the Trigger.

The stability of the Xo frequencies over a longer span of time (days, weeks) has been assessed satisfactorily with the 2 available prototypes and it is therefore expected that such adjustment work on the Xos is not needed regularly. For a rapid estimation of this effect please note that a differential of 1E-5 between two Xos results in a 0.5us offset after 50millisec (i.e. half a Booster orbit turn after the full acceleration cycle).

It is further noted that the Booster RF frequency is completely identical to that of the Storage Ring, and the latter has daily fluctuations of about 20Hz (i.e. 6E-8) due to (12hrs) tidal effects, and long-term variations of about 200Hz (6E-7).

RESOLUTION, REPRODUCIBILITY AND SIGNAL LEVEL DEPENDANCY

The 2 prototypes have first been measured in the laboratory with a CW RF signal source on their performance of resolution, reproducibility and long-term stability, and their dependence of the beam position values on the RF signal strength at the 4 inputs.

For this the input signal level was programmed with steps of 5dB from -70dB to -40dBm (every 100sec), and a record of 1600 values (0.1sec) of the X and Z buffers (64-decimated-TbT, i.e. 16KHz rate) was taken every 2sec. The average and rms values were calculated on each buffer (with K-factor at 10mm), and this yields 50 values at each distinct level. The whole measurement sequence was repeated for >20hours so to also assess any slow drifts of these position readings. The Fig.4 illustrates only one such sequence covering a period of 700*2=1400sec (23min). The top plot shows the sum signal recorded while the two middle plots the X and Z values (for each prototype), and the bottom plot the 4 rms noise values (X & Z, both units).

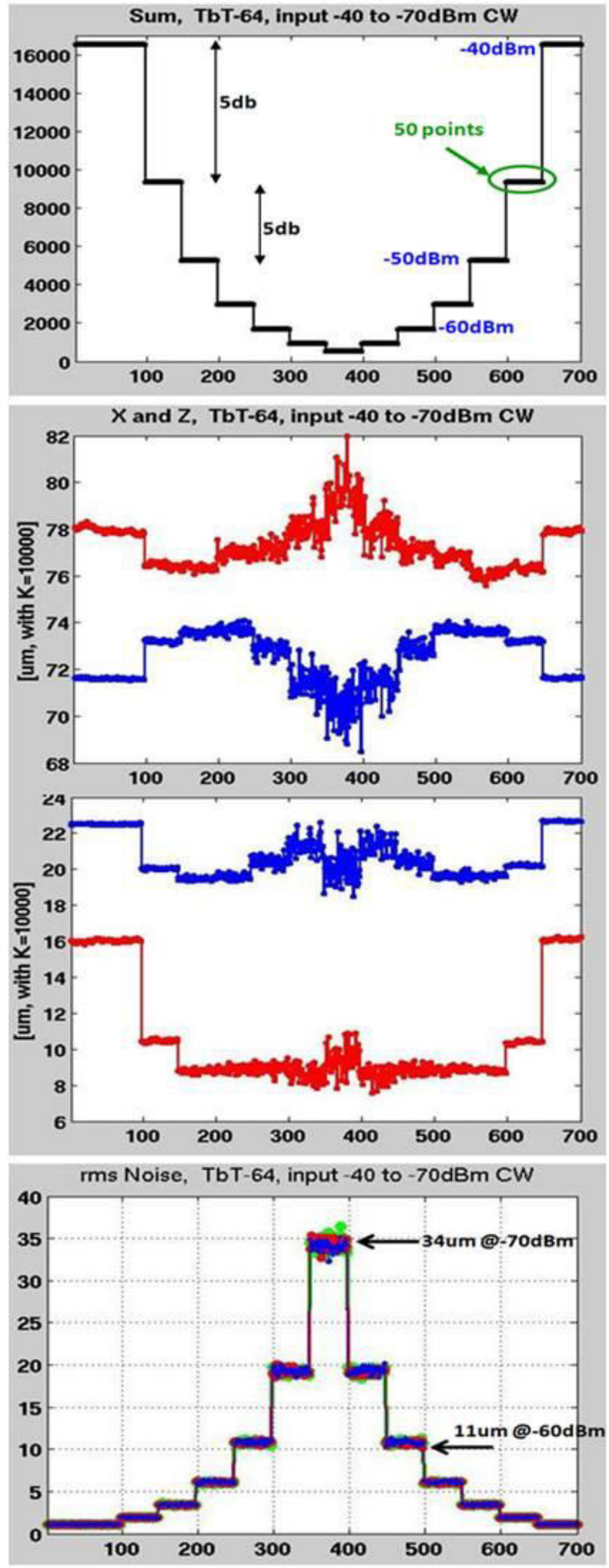

Figure 4: recordings over 23min showing from top to bottom values of Sum (i.e. Signal Level), X (blue) and Z (red) of both units, and rms noise. All data taken from the 16KHz rate buffers and with CW RF power at inputs, and with K-factor at 10mm.

The results can be resumed by the following figures : The shift of beam position value due to a different level of RF input signal (also called Beam-Current-Dependence) is 3, 3, 3, 8um (x1, x2, z1, z2) for -40 to -70dBm.

The noise (for 16KHz rate output) is 1.1, 3.4, 11 and 34 um rms (average of X & Z) for input levels of respectively -70, -60, -50, -40dBm.

As stated above, the measurement sequence was continued for more than 20hours to also assess any drifts over such a time-span. Such drifts were in the order of 1um (rms) on both units, for both planes.

TURN-BY-TURN MEASUREMENTS IN EARLY CYCLE OF THE BOOSTER

The 2 units have been connected to two Booster BPM blocks using RF cable lengths of about 20m. This allowed verifying the signal levels and some general performance aspects. This also made it possible to measure the beam position directly after the injection of a single bunch (0.1mA current) into the Booster, and on the 1MHz Turn-by-Turn rate and also using the MAF filtering as described above. The latter assures the acquisition of true (i.e.no-smearing between turns) T-b-T position data with the best noise performance.

The betatron tune values of the beam oscillations can be calculated by a simple FFT on that T-b-T data. It was done in slices of 1000 Turns (i.e. 1millisec), and over the first 8millisec after injection. In Fig.5 an image of such tune data (from 1 BPM) shows of a single injection the excursions of both tunes visible over this 8ms period.

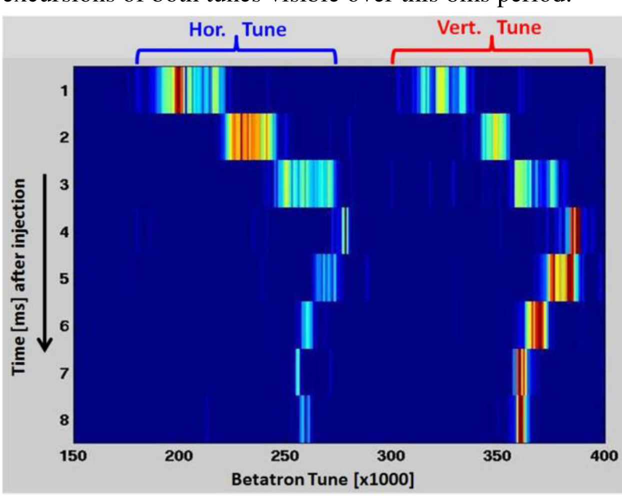

Figure 5: The tune behaviour in both planes of the injected beam during the first 8ms, in 8 slices of 1ms.

When repeating such tune measurements at successive injections the shot-to-shot stability of the Booster's magnet currents can be assessed. Obtained results are shown in Fig.6 over 40 shots with 2 independent BPMs (and Sparks) measuring the horizontal tune at 4ms after injection, in a window of 1ms. The result difference between the two systems is typically below 5E-4 (on a tune of ~0.27).

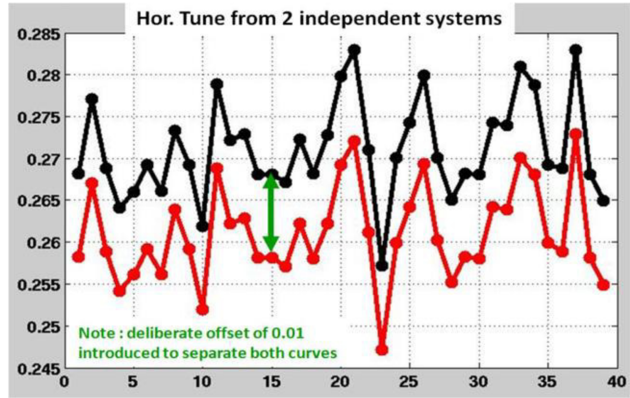

Figure 6: The horizontal tune stability, measured by 2 independent BPMs, over 40 shots at 4ms after injection.

INSTALLATION OF A FULL SYSTEM AND FURTHER DEVELOPMENTS

End of this year 75 units will be installed progressively. Their installation inside the Booster tunnel with short (2m) RF cables from their BPMs is considered but not yet decided. Radiation dosimetry measurements are performed since a few months at specific points to help such decision, while also similar electronics have been exposed since months and are being monitored for any malfunctioning caused by received dose. If the risk of radiation damage is judged too high then installation outside the tunnel is possible but at the expense of lower sensitivity and higher noise levels.

The satisfaction with these prototypes has stimulated the conception of a more complete device that includes a PLL, variable RF attenuators and a 40Hz data-stream output (not depending on triggering). The realisation is presently undertaken and will be available in early 2015.

ACKNOWLEDGMENT

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