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IMPROVEMENTS ON THE LHC INTERLOCK BPM SYSTEM

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Abstract

The LHC interlock BPM system is used as part of the beam abort system to insure that beam trajectories in those regions are conform with a safe extraction of the beams from the main ring to the dump lines.

After more than 10 years of operation, the system has shown some limitations in bandwidth and dynamic range and a study was initiated to look for improvements.

Nowadays, with the availability of multi giga sample per second sampling rate ADC converters, there is potential to greatly improve the performance of the system.

In this paper a wideband architecture with direct acquisition of the BPM electrode signals, time interleaved on the same read-out channel is presented with emphasis on the design and construction of the critical components, and on the measured performance of a prototype system tested in the LHC during the 2022 run.

INTRODUCTION

The LHC interlock beam position system (BPM) is a redundant safety system using eight stripline pickups. It measures the transverse beam position on a bunch-by-bunch and turn-by-turn basis, and for each bunch it counts the number of times the measured position is outside a defined acceptance range for a given number of turns. If that value exceeds the given threshold, the system triggers a safe beam dump request. Indeed, if the bunches would travel on a trajectory too far off the nominal orbit, they would be directed outside the dump line by the kickers, hitting elements of the machine risking to damage them. While the system is required to protect the machine, it should not generate false triggers causing downtime for the LHC physics program.

The operational interlock BPM uses the same hardware as the standard trajectory LHC BPM with the Wide Band Time Normalizer (WBTN) as analogue front-end. [1]

The main reason for developing a new interlock BPM system was the use in LHC of the so called "doublets bunches", a beam format with pairs of bunches spaced by 5 ns, to be used for scrubbing. Because of bandwidth limitation, the WBTN system is unable to reliably measure the beam position for this beam format. Today, even if these "doublet" bunches are not anymore foreseen in the LHC, the proposed architecture is a valuable proof of principle for a future consolidation of the LHC BPM system, of which the interlock BPM system will be part.

New LHC interlock BPM test system

The new system (Fig. 1) is based on two main features:

- Time interleaving of the two BPM electrode signals of one plane: the signal of one electrode is delayed and combined with the signal from the opposite electrode before further processing
- Direct sampling at a rate of 2.6 giga samples per second (GSPS)

This architecture has two advantages. First, it removes almost all errors due to asymmetries in the read-out system, including imperfections, tolerances, aging effects, etc., as it presents a single channel read-out for the two symmetric BPM pickup electrodes. While these errors can in principle be continuously measured and corrected with the use of a calibration signal, the long beam storage duration of the LHC luminosity runs, 8 to 12 hours, limits the effectiveness of this approach. The second advantage, in terms of cost and space, is the reduction of the number of measurement channels by a factor 2.

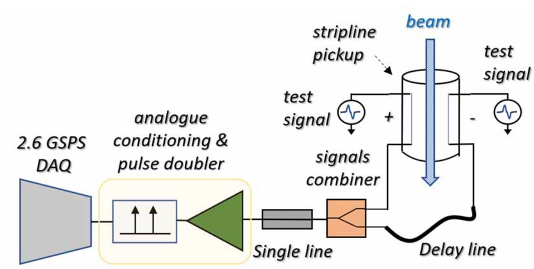

Figure 1: Proposed LHC interlock BPM system.

The direct sampling at 2.6 GSPS leads naturally to a much wider system bandwidth without compromising the dynamic range, thanks to the availability of high resolution, fast sampling ADCs. The dynamic range, here the range of beam intensities where the system resolution is better than the required limit, is indeed also an important feature since it is related to the probability of a false trigger with bunches of different charge being present in the stored beam.

The downstream port of the stripline-electrode is used to inject a synthetic beam pulse for system testing purposes. This allows to verify the correct functioning of the entire acquisition chain at the start of each LHC run cycle.

Since the building blocks of the analogue signal acquisition chain for the proposed architecture are not available as off the shelf components, a custom design was made.

PICKUP SIGNAL

The requirements for the system components have been calculated based on the interlock BPM specifications (Table 1) and the characteristics of the pickup (Table 2).

The stripline pickup (PU) used for the interlock BPM system has been simulated with *CST Studio* and the results

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are very close to actual measurements taken with a high bandwidth oscilloscope [2].

The calculated total power from one electrode into a 50 Ω load, for the machine filled with 2808 bunches, each 2.7e11 particles, is in the order of 20 W. Most of the signal power reaching the analogue receiver after the ~50 m long coaxial cable is in the frequency range between 20 MHz and 1.2 GHz, with a peak between 500 and 600 MHz, given by the convolution of the stripline response with the response of the cable.

Table 1: LHC Interlock BPM Specifications. [3]

Parameter	**Min**	**Max**
Beam intensity [ppb]	5e9	2.7e11
N. of bunches	1	2808
Bunch distance [ns]	25	
Bunch length RMS [ns]	0.8	2
Typ. interlock threshold [mm]	-3	3
Interlock system resolution [mm]		0.2

Table 2: Stripline Pickup Specifications

Parameter	**Value**
Aperture [mm]	80 / 130
Stripline length [mm]	120
Stripline width [mm]	12.3

ANALOGUE DESIGN

The main features of the custom-built power combiner are:

- Bandwidth: 20 MHz … 1.5 GHz
- Max. total input power: 20 W
- Port return loss: >20 dB
- Input port isolation: >30 dB
- Input port balance: < +/-0.3 dB

The bandwidth covers most of the beam signal power, and the power rating is half the maximum power delivered to the combiner by the ultimate proton HL-LHC beam (2 x 20 W). To be compatible with such high intensity beam a 3 dB attenuator rated 20 W is foreseen on both input ports.

The design is based on a resistive bridge with a ferrite loaded coaxial cable acting as balun transformer (Fig. 2).

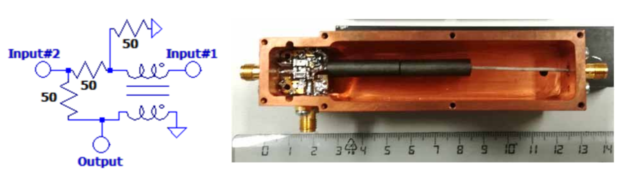

Figure 2: Resistive bridge power combiner [4]. Schematic(left) and actual device with ruler in cm (right).

This solution provides good broadband impedance matching on all ports and high isolation between the input ports but has 3 dB excess loss compared to a “classical” RF power combiner. Half of the input power is therefore dissipated into the internal resistors and an appropriate heat sink must be provided.

The flatness of the balance between the input ports is important to minimize the position measurement dependency on the beam signal frequency spectrum, i.e., the dependency on the longitudinal bunch shape.

To increase the number of meaningful samples from the ADC for each bunch, exploiting the intra-bunch region where no signal is present (Fig. 3), a pulse-doubling filter has been designed, based on the principle shown in Fig. 4.

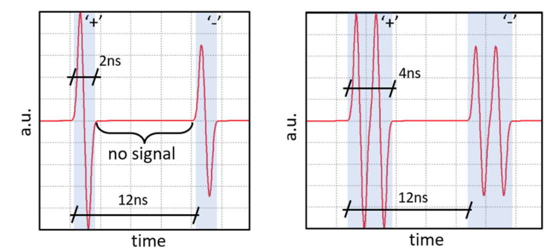

Figure 3: Ideal signals after the power combiner (left) and after the pulse doubler(right).

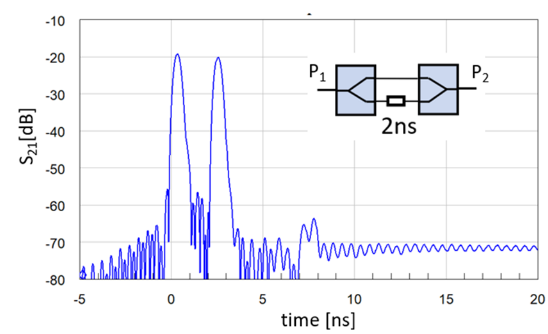

Figure 4: Pulse doubler time domain response.

The two power splitter/combiner of the pulse doubler are based on the same principle as the electrode signal combiner (Fig. 2) but in this case the balun is a commercial surface mount (SMT) component. A good impedance matching on all ports is mandatory to avoid reflections that would cause signal interference and cause power leaking between the two BPM electrode signals. A practical measure to quantify and control this effect is the impulse response through the time domain transform of S_{21} (Fig. 4).

POSITION MEASUREMENT

The measurement of the beam position is based on the delta over sigma normalization in Eq. (1) [5]

$$position = \boldsymbol{k} \cdot \frac{a_+ - a_-}{a_+ + a_-} \tag{1}$$

with $\boldsymbol{k}$ the scaling factor depending on the PU geometry.

The amplitudes of ‘+’ and ‘-’ signals (i.e., a_+ and a_-) are evaluated by computing the convolution (Eq. 2) of the received signal s_{FULL} with the ‘+‘ signal (Fig. 5 right) s_+. The result of the convolution is plotted in Fig. 5. This resembles a matched filter with s_+ as filter template. The matched

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filter is well known for maximizing the signal to noise ratio in the presence of additive white gaussian noise [6].

$$c(x) = \sum_{k=0}^{n} s_+(x-k) \cdot s_{FULL}(k) \quad (2)$$

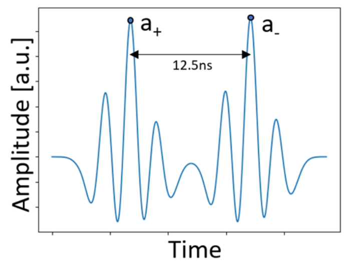

Figure 5: Convolution result of an LHC bunch.

The amplitudes of the '+' and '-' signals correspond to the peaks in the convolution waveform.

The resolution has been evaluated by injecting a test signals (see Fig. 1) and comparing it with the theoretical value expected from a white noise equivalent to the ADC noise level as from specifications [7] (Fig. 6).

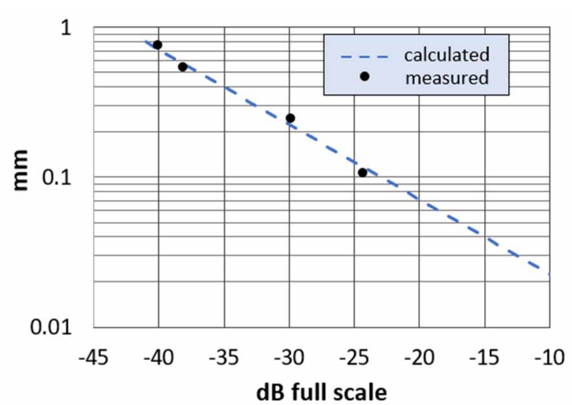

Figure 6: Position resolution vs signal amplitude.

As result the system demonstrates a single bunch measurement resolution better than 0.2 mm over a dynamic range of the input signal amplitude exceeding 20 dB taking in account 6 dB headroom from the ADC saturation.

Accuracy and linearity have been evaluated in laboratory measurements using the setup shown in Fig. 7 for three attenuation values: 0 dB, 2.86 dB and 4.84 dB (corresponding to beam displacements of 0, ~4, and ~7 mm) at fixed output level of the test generator corresponding roughly to -3, -6, -12 and -18 dB ADC full scale (FS) range. The error in case of the 80 mm aperture pickup is up to 0.3 mm.

The linear part of the interference of the signal from the '+' electrode to that of the '-' electrode, due to a not ideal test signal and to reflections in the acquisition chain can be modelled in a simplistic way as

$$a_{-(measured)} = a_- + k \cdot a_+ \quad (3)$$

with k = -0.027. The accuracy measurements corrected using Eq. (3) are shown in Fig. 8.

Contributions to the residual error raise from ADC non-linearities and the insertion loss repeatability of the attenuators. At -3 dBFS level, the increased error could be explained by a signal amplitude compression of a few hundredth dB. This is compatible with the +10 dBm output power at 0.1 dB compression measured for the class A amplifier stage driving the ADC.

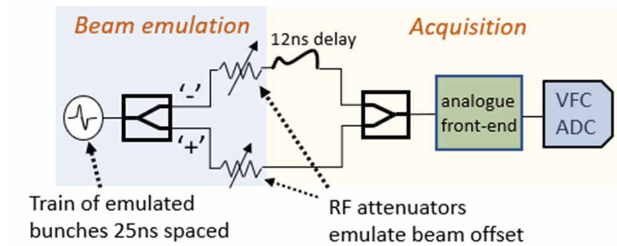

Figure 7: Accuracy measurement setup.

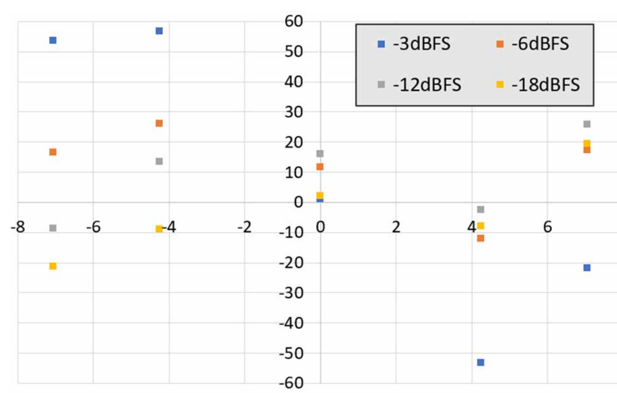

Figure 8: Position error in µm (Y) vs. simulated position in mm (80 mm PU) after interference and offset removal.

LHC BEAM MEASUREMENTS

One test system was installed in LHC tunnel early 2022 and position measurements were taken during the 2022 run. Worth of notice is the standard deviation of 25 µm measured with a proton beam at the intensity of ~1.2e11 particles per bunch (ppb) in the flat-top region of a LHC run. The standard deviation measured for the same beam with the operational system is about 100 µm.

CONCLUSIONS

A new approach to measure the bunch-by-bunch beam position in the LHC has been developed and both, advantages and limitations have been presented. The performances of the analogue blocks are critical to reach the required performance; in particular the power rating and the port balance of the signal combiner, the reflections in the signal chain and the linearity of the active components require special attention.

The measurement results of the proposed system improve the measurement performance set by the present WBTN system, utilizing a higher available bandwidth compatible with the "doublets" beam format. However, no measurements could be performed to evaluate the performances with doublet bunches.

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