BEAM TEST PERFORMANCE OF THE BEAM POSITION MONITORS FOR THE TBL LINE OF THE CTF3 AT CERN *

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Abstract

A series of Inductive Pick-Ups (IPU) for Beam Position Monitoring (BPM) with its associated electronics were designed, constructed and tested at IFIC. A full set of 16 BPMs, so called BPS units, were successfully installed in the Test Beam Line (TBL) of the CLIC Test Facility (CTF3) at CERN. In this paper we present the results of the beam test carried out on the BPS units of the TBL in order to determine their beam performances and check the specified operational requirements. We focus particularly on the position resolution parameter which is the BPS figure of merit according to TBL demands and is expected to reach the 5 μm resolution at maximum beam current (28 A). The beam test results of the BPS units are also compared with the parameters from their previous characterization test at lab.

INTRODUCTION

The CTF3 will demonstrate the essential parts of the CLIC drive beam generation scheme consisting of a fully loaded linac, a delay loop and a combiner ring. The final CTF3 drive beam is delivered to the CLIC Experimental Area (CLEX) comprising the TBL and the Two Beam Test Stand (TBTS). The TBL is designed to study and validate the CLIC drive beam stability during deceleration in the power extraction process. The TBL consists of a series of FODO lattice cells and a diagnostic section at the beginning and at the end of the line to determine the relevant beam parameters. Each of the 16 cells in TBL with a 1.4 m length per cell is comprised of a quadrupole, a BPS and a Power Extraction and Transfer Structure (PETS) that will produce the nominal CLIC power of 135 MW with a 28 A beam current [1].

The BPS monitor is an Inductive Pick-Up and the expected performances are a resolution at maximum current below 5 μm and an overall precision (or accuracy) less than 50 μm, for a TBL beam type of current range 1-28 A, energy 150 MeV, emittance 150 μm, bunch train duration 20-140 ns, microbunch spacing 83 ps (12 GHz), microbunch duration 4-20 ps and microbunch charge 0.6-2.7 nC. The main benefits argued for using IPUs in the TBL are: position and current intensity measurements in the same device, less perturbed from the high losses in linacs, high output dynamic range for beam currents in the range of interest, broad bandwidth for pulsed beams and short total length.

It is essential for CLIC an efficient and stable 12 GHz power production, so the experimental program of TBL is focused on 12 GHz power production and the transport of the decelerated beam [2]. In order to insure proper beam transport through the line, the quadrupoles have to be aligned within 10 μm by beam-based alignment demanding to the BPS units a 5 μm position resolution for a beam with 28 A maximum current [3]. Thereby the resolution parameter is considered the BPS figure of merit and here is presented the method and results of the beam test carried out in July 2011 for determining it at different beam currents.

THE BPS MONITOR AND TEST BENCHMARKS

Basic Operation Mechanism

The BPS inner vacuum pipe of 24 mm aperture has a ceramic gap surrounded by gold plated cylinder which is divived along into four orthogonal strip electrodes. The wall current intensity induced by the beam flows through these electrodes at bigger wall diameter, and the beam position is measured by means of the image current distribution among these electrodes that will change according to the beam proximity to them. Thus the current level in each electrode is sensed inductively by their respective transformers, which are mounted on two internal PCB halves as part of the electrode outputs conditioning circuit. The horizontal and vertical coordinate positions are given by each pair of strip electrodes in the horizontal and vertical planes of the BPS. From the PCB circuits, the output SMA connectors give four voltage signals (V_+, H_+, V_-, H_-) that will drive an external amplifier to yield the three signals for determining the beam position and intensity: the sum signal $\Sigma = V_+ + H_+ + V_- + H_+$), to get the beam current intensity; and two difference signals ($\Delta V = V_+ - V_-$ and $\Delta H = H_+ - H_-$) which are proportional to the horizontal and vertical coordinates of the beam position. Finally, at the digitizer end the coordinates data are obtained from several amplitude samples within the normalized pulse signals as, $x_{H,V} \propto \Delta H, V/\Sigma$ (see Eq.(1)). A detailed description of the BPS-IPU monitor can be found in [4].

Characterization Test Parameters

Every BPS unit must be characterized by its specific parameters for the correct beam position determination and they need to fulfill the specifications given for TBL. The normalized $\Delta H, V/\Sigma$ signals have to show a good linear behavior for the beam position variation within the ±5 mm central region of the BPS aperture, so these output signals will be related to the beam position components by the fol-

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lowing linear relation:

$$\frac{\Delta H, V}{\Sigma} = S_{H,V}\, x_{H,V} + n_{H,V} \qquad (1)$$

The operation parameters of these relations are obtained from the characterization tests at lab. These tests are based on a specific designed test stand which allows moving the BPS under test with respect to a thin and stretched wire carrying the excitation current and emulating the beam passing through the BPS [4],[5]. The sensitivity or linearity test is performed on the test stand by acquiring the wire $x_{H,V}$ position coordinates from a high precision movers, and the $\Delta H, V$ and Σ signals coming from the analog amplifier connected to the BPS output signals. A linear fit on these data for each position was done to get the sensitivity parameter for each coordinate, $S_{H,V}$, as shown in the Eq.(1). The intercept $n_{H,V}$ is related with the electric offsets from the true BPS mechanical center or zero position.

Concerning the position measurement performance there are two main parameters the overall precision or accuracy and the resolution. The accuracy can be seen as the uncertainty in measuring an absolute position with respect to a known reference. In contrast, the resolution represents the uncertainty in measuring a relative position increment being limited by several sources of system noise in the signals used to measure the position. The accuracy in the BPS is determined as the root mean square of the horizontal and vertical position deviations from the linear fits in the range of interest. The analysis performed on the data from this lab characterization test yield a benchmark accuracy of 32 μm and 28 μm (averaged over all BPS units in TBL) for the horizontal and vertical coordinates which are under the 50 μm specification. The results of sensitivity, offset and accuracy parameters for all the 16 BPS units measured at lab can be found in [5].
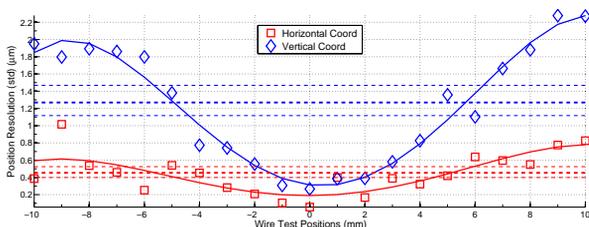

Figure 1: Resolution vs. position for BPS0510 in the ±10 mm range.

In order to measure the BPS resolution in the test stand, it has been also analyzed the data for all the BPS units taken before their installation in TBL in the characterization tests at lab. In the Fig. 1 is shown the resolution points as the standard deviation of scattered positions at each wire nominal position. The resolution parameter is then given as the standard deviation for all the scattered positions in the full ±10 mm range. The same behavior of the resolution parameter depending on position was observed in the rest of the tested monitors. Resolution improves towards the center of the monitor having the minimum value at the electrical center. This is because the difference signal $\Delta H, V$, from which the position is calculated, cancels as it also does the

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external noise. The resolution parameter at wire current of 57 mA, and particularly for the BPS tested with beam, is 0.6 μm and 1.4 μm in the BPS0510, for the horizontal and vertical coordinates respectively (shown in the plot as dashed lines). These resolution levels were obtained for a low noise test stand with a very precise excitation signal of 1 MHz generated with a Vector Network Analyzer. This resolution parameter sets the lowest limit that could be achieved with a BPS, and it can be considered as test benchmark.
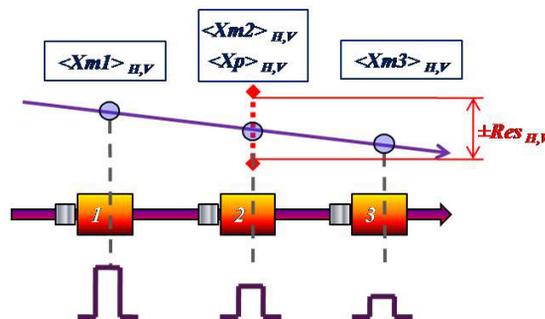

Figure 2: Illustration of the 3-BPM's resolution method.

RESOLUTION BEAM TEST

Since the beam positions have jitter from pulse to pulse shots in a beam line, the BPS resolution can not be determined with measurements taken in a single BPS, in contrast to the resolution measured in the characterization test stand where the wire emulating the beam can be set to a fixed position. For that reason, the resolution beam test method illustrated in Fig. 2 is based on the measurements of beam positions on three consecutive BPS units in order to obtain the position resolution of the central BPS from several beam pulse shots and taking out the beam jitter contribution. A straight beam trajectory, without significant beam current loss, can be set across the three BPSs section by switching-off the steering quadrupoles around this section. Thus, from the position measurements of the two side BPSs the beam position in the central BPS is obtained by interpolating it in the beam straight path and compared to its own reading. The difference of the interpolated and the measured beam positions in this BPS, after substracting the relative mechanical offset, reflects only the system noise uncertainty in the position readings having removed the beam jitter influence. Finally, the resolution of the central BPS can be obtained as the standard deviation (or the rms) of this difference for many beam pulse shots.

The main aim of this beam test was to evaluate the beam position resolution that could be achieved in TBL for different beam currents. At the moment of the beam test four TBL modules in the beginning of the line were fully equipped with their respective PETS tanks. Therefore, the next available BPS units for resolution measurements were located downstream just after these modules to avoid unknown influence of the PETS. It was acquired relevant

data from a total three consecutive BPS units (labeled as BPS0450, BPS0510 and BPS0550) being able to evaluate the resolution independently on the central BPS with its respective side monitors, according to the previous method. The present maximum beam current entering in TBL from the CTF3 combiner ring is around 13 A corresponding to a recombination factor four, then it was chosen four beam currents with increasing recombination factor to observe the behavior of the resolution in function of the current.

For each beam current, it was acquired the entire pulsed waveforms of the beam current and the horizontal and vertical positions in the four mentioned monitors for 200 beam pulse shots with a repetition rate of 1Hz and pulse length of 280 ns. The current and coordinate positions were averaged within their pulse signal samples in a time gate of about 230 ns (46 ADC samples at 5 ns per sample) removing the sharp pulse flanges. Then, taking the set of three BPS, the resolution was calculated in the respective central monitor, BPS0510, using their pulse averaged positions as described in the previous method. A gaussian fit was performed on the values of the difference between interpolated and measured positions taking the standard deviation as a measure of resolution, matching up with the rms measure, and calculating also the confidence intervals for that resolution point. In Fig. 3 it is shown the resolution histogram and the gaussian fit of the BPS0510 at maximum available current of 12 A, having the best resolution for the vertical coordinate of 11.9 µm in a [10.8, 13.2] µm 95 % confidence interval, while for the horizontal coordinate is 65.4 µm and [59.5, 72.5] µm for the same confidence interval.

Finally, as depicted in Fig. 4, each of the resolution points was evaluated like in the analysis shown in Fig. 3, and they were obtained for the selected monitor and currents in the horizontal and vertical coordinates. The set of four nominal beam currents was [3.5 A, 7 A, 10 A, 13 A] although arriving lower current levels at the location of the monitors under test due to beam transport losses. As expected, higher beam current improves the resolution leading to lower values because of the better signal to noise ratio. A fit has been performed to these resolution points to show their linear scaling with current for both position coordinates. The 95 % confidence intervals for those resolution points calculated previously are also depicted. The linear fit is used to extrapolate the resolution points to higher currents beyond the measured ones. As a result it can be observed the strong tendency and a good outlook to achieve the 5 µm resolution goal at the nominal maximum beam current of 28 A for both coordinates. The significant difference between the horizontal and vertical coordinates indicates that the resolution levels had also contributions from the additional noise in the BPS signals most likely due to beam losses. Moreover the 10-bits resolution ADC's jointly with the BPS signal levels at the ADC input set a quantization step corresponding to a 10 µm beam position step, biasing also the measured position resolution levels. Since the beam quality can still be improved much more, it turns to be in favor to reach the desired BPS resolution.
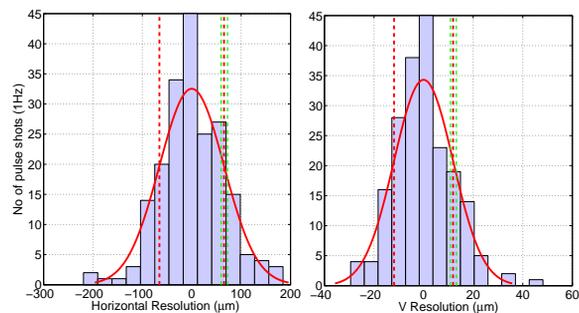
Figure 3: Resolution (red dashed) and its 95 % confidence interval (green dashed) for the BPS0510 coordinates at 12 A beam current.
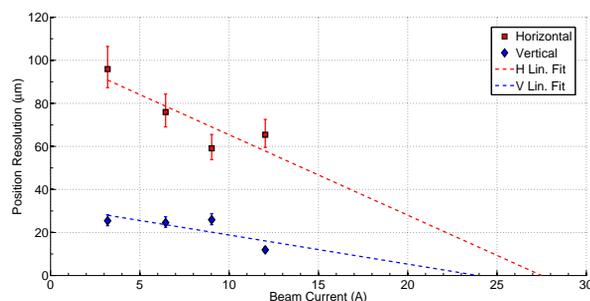

Figure 4: Resolution vs. beam current for BPS0510.

CONCLUSIONS

A beam test was performed in TBL to study the evolution of the resolution with different beam currents and for two consecutive BPS units. The minimum resolution observed was 11.9 µm at the maximum available beam current of 12 A. The performed estimation for the resolution at the 28 A nominal beam current shows that eventually the 5 µm specification goal could be achieved at this current.

ACKNOWLEDGMENTS

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