TOWARDS SUB-MICROMETER RESOLUTION OF SINGLE SHOT STRIP LINE BPM *

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Abstract

A high resolution single shot BPM set-up is designed. One of the BPM modifications is developed as a difference-sum BPM based on strip line pickup. In this BPM, each strip line signal is converted in a time domain converter into a three 660MHz-wave burst. The difference and sum bursts produced by a hybrid junction are detected in a pair of synchronous detectors. The synchronous detector reference signals, and ADCs clock triggers are manufactured from the sum burst. The set-up and features of this BPM are presented. The BPM resolution was measured using a KEK ATF beam. For equivalent bunch intensity 0.3nC the resolution is about 1μm (for BPM effective aperture 1/5). With appropriate ADCs, this BPM can measure individual bunches at a rate of up to 50MHz. The BPM latency to the ADC inputs is as low as 10ns. High resolution and low latency together, make this BPM suitable for fast feedback/feed-forward systems.

INTRODUCTION

In this paper, some results of the development of a single shot BPM, based on an electrode pickup, are described. The development of this device was driven by challenging beam diagnostics requirements for the ILC, ATF2 [1,2], and the EMMA [3] accelerators.

The BPM should meet the following requirements:

- Bunch charge: 1nC (ATF2); 0.01– 0.1nC (EMMA).
- Bunch spacing (a getting-ready-to-the-next-bunch time): 300–150ns (ATF2); 50ns (EMMA).
- Vacuum chamber aperture: 25mm (ATF2); 40mm (EMMA).
- Beam position measurement range: a few mm (ATF2); a full aperture (EMMA).
- Pickup: strip line electrodes (ATF2); button electrodes (EMMA).
- Resolution: $\leq 1\mu m$ (ATF2); $\leq 50\mu m$ (EMMA, 30pC).
- Analog processing latency: $<< 150ns$ (ATF2).

An attempt was made to develop a processing scheme and a corresponding to it set of matching circuits that could be combined into some 'optimal' single shot BPM that would meet the requirements above, in particular, which would have highest resolution in a full pickup aperture or, within a reasonably reduced position range, a resolution close to the thermal noise resolution limit. A BPM modification for the EMMA is now under design. Here we focus at a BPM modification that was meant for The ILC crab Cavity Test Bench [1] and Feed-Forward Correction System [2] at the ILC/ATF2.

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DIFFERENCE-SUM BPM SET-UP

In the BPM, each strip line pickup signal is converted to a flat-top-envelope three-wave burst. The difference and sum bursts from the outputs of a hybrid junction are amplified and detected in a pair of synchronous detectors. The output of each detector is smoothed with a LP filter and sampled at its end flat part by an ADC.

A short burst with a flat top envelope is an important feature of the BPM. With it, three goals are attained: first, the BPM gets a short getting-ready-to-the-next-bunch time; next, it has a short latency as the filter output that is sampled at its end is of the same length as the burst; finally, with an envelope flat top and using an overshot-less Gaussian filter, it is possible to obtain in a short burst time a BPM output pulse with a flat end. The flatness at the sample moment is significant as it enables to reduce additional noise generated by ADC clock jitter, and to relax the tolerance of sample moment positioning as well.

An initial variant of a pickup-signal-to-burst converter [5] was based on an irregular strip line coupler described in [6]. A coupler's wave was split into four waves each of which was progressively delayed and then re-combined.

Later a more compact variant was developed as a 50Ω time domain converter consisting of three cascades each of which is a single wave coupler analogous to the device mentioned above. The converter is made as a PCB with a pair of coupled strip lines between two ground planes. To get a flat envelope in a converter of such kind, it is necessary in the design to adjust the coupling strengths in the first two cascades to have them matched to the last cascade.

In this converter, the wave half-period is made equal to the spacing of the delta function pulses in the strip line pickup signal. Starting with the second half-wave in the burst, the magnitude is doubled as the waves excited by the pickup's opposite polarity pulses are summed with opposite phases. The last half-wave is similar to the first half-wave. So, the burst envelope has a trapezoidal shape. The beam signal magnitude on the flat top is about 0.7V for a bunch intensity of 1nC.

Another method of converting a strip line pickup signal into a flat top envelope burst is described in [7].

The BPM is based on difference-sum 0.01–2GHz hybrid junction H-9 (from Anzac–M/A-Com). We don't consider here a problem of BPM zero offset stability and zero offset adjustment methods and procedures.

The BPM analog outputs are measured with a pair of ADCs. Bunch intensity normalisation is supposed to be done in a digital post-processor. Sum of BPM analog processing time, ADC measurement time and normalisation time amounts to a total BPM latency. The BPM processing time is about 10ns. With a commercial pipeline 100MHz ADC, its output is available after 3 (ADS5424) or 4 (AD6645) clock cycles. So, the BPM latency without normalisation equates to 40–50ns.

In this BPM, an attempt was made to make it autonomous. It has an internal beam-based synchronisation. The synchronous detector reference signal is produced by an internal circuit from the sum burst as a synchronous burst of regular amplitude. Another circuit triggered by the synchronous burst generates the ADC clock.

DIFFERENCE-SUM BPM RESOLUTION

I. For the signal magnitudes V_d, V_s at the difference-sum junction outputs the beam position Y is calculated as

$$Y = R_{eff}(g_s / g_d)(V_d / V_s) \quad (1)$$

where R_{eff} is the effective pickup radius, g_d and g_s are the junction voltage gains for the matching output loads r. For the junction output thermal noise voltage $\sqrt{<u^2>} = \sqrt{4kTB \cdot (r/2)}$ the resolution can be written as

$$\sqrt{<y^2>}\Big|_{limit} = R_{eff} \frac{g_s}{g_d} \cdot \frac{\sqrt{<u^2>}}{\bar{V}_s} \sqrt{1 + \left(\frac{\bar{Y}}{R_{eff}(g_s / g_d)} \right)^2} \quad (2)$$

where $\bar{V}_s$ and $\bar{Y}$ are mean values. The expression (2) gives **a BPM resolution lower limit** for a position measurement range $R_{eff}(g_s / g_d)$. The limit is inversely proportional to beam intensity and grows with beam offset (for $g_d = g_s$ up to $\sqrt{2}$ times for $\bar{Y} = R_{eff}$). Estimation of (2) for $R_{eff} = 9\text{mm}$, $\bar{V}_s = 0.7\text{V}$, $\bar{Y} = 0$, $r = 50\Omega$ and $B = 150\text{MHz}$ ($\sqrt{<u^2>} \approx 8\mu\text{V}$) gives $\sqrt{<y^2>}\Big|_{limit} = 100\text{nm}$. With this limit, **the BPM ultimate range** $\Re$ defined as $\Re = \sqrt{<y^2>}\Big|_{limit} / R_{eff} \cdot (g_s / g_d) = = \sqrt{<u^2>} / V_s$, is (–99)dB.

II. Assume the signals V_d, V_s are amplified and then detected. The amplifier and detector gains and noise factors are respectively G_A, F_A and G_D, F_D. The resolution $\sqrt{<y^2>}\Big|_D$ at the detector output can be written as

$$\sqrt{<y^2>}\Big|_D = = R_{eff} \frac{g_s G_s}{g_d G_d} \cdot \frac{G_d \sqrt{<u^2>}}{V_s\big|_D} \sqrt{F_d + F_s \left(\frac{\bar{Y}}{R_{eff}(g_s / g_d)} \right)^2} \quad (3)$$

where each total gain is $G = G_A \cdot G_D$ and each noise factor is $F = F_A + (F_D - 1) / G_A^{\,2}$.

The expression (3) represents evolution of the thermal noise. However, other kinds of noise may appear in the signal path. Consider here one of them. Assuming that for a BPM input signal as a sine wave burst a synchronous detector is used where the switches are commutated by a square wave reference signal. Equating the detector to a multiplier and introducing a reference jitter $|\delta t_{ref}| << T$, where T is the period, one can calculate a detector voltage output V as

$$V = (2a / \pi)[1 - 2\pi^2 (\delta t_{ref}^{\,2} / T^2)] \quad (4)$$

where for the reference signal magnitude taken equal to 1 the input wave amplitude is $a \le 1$. The first term is the detected signal, the second term with δt_{ref} randomly changing from shot to shot is an additional voltage noise. This noise, first, is proportional to the input signal strength, second, it is a non-linear transformation product of the reference signal jitter. For Gaussian jitter, this noise in non-gaussian: it has a DC component, it is limited on one side with zero and on the other side has large fluctuations.

For an 'optimal' BPM this noise should not exceed the thermal noise. For a full aperture BPM with $g_d = g_s$, taking maximal beam offset as $\bar{Y} = R_{eff}$ and the detector output range as $\Re \cdot \sqrt{F_d + F_s}$ one can write:

$$\delta t_{ref} / T \le (1/\pi) \sqrt{\Re \cdot \sqrt{F_d + F_s} / 2} \quad (5)$$

Estimation of (5) for $\Re = (-99)\text{dB}$ and $F_d = F_s = 1.6$ gives $\delta t_{ref} / T \le 1 \cdot 10^{-3}$.

III. With a buffer amplifier at the detector output, the noise-to-signal range at the ADC input can be written as $\Re \cdot \sqrt{F_{d\,tot} + F_{s\,tot}}$, where each total noise factor is:

$$F = F_A + (F_D - 1) / G_A^{\,2} + (F_{B\,eff} - 1) / G_A^{\,2} G_D^{\,2} \quad (6)$$

with a buffer effective noise factor taken as $F_{B\,eff}$. For an 'optimal' ADC, its resolution defined as $\alpha_1 \alpha_2 / (2^n - 1)$ where n is the number of bits, and $\alpha_1 \ge 1$, $\alpha_2 \ge 1$ are some coefficients, should satisfy the condition

$$\alpha_1 \alpha_2 / 2^n \le \Re \sqrt{F_{d\,tot} + F_{s\,tot}} \quad (7)$$

For $\Re = (-99)\text{dB}$, $F_{d\,tot} = F_{s\,tot} = 2.5$, and $\alpha_1 = \alpha_2 = 1$ the number of bits is $n \ge 16$.

The coefficient α_1 is introduced to take into account the ADC transition noise. The coefficient is a rms quantity expressed with the LSB units. The coefficient α_2 is used to take into account the ADC clock jitter. For a flat top BPM output pulse the coefficient is $\alpha_2 = 1$. For a simplest case of linear slope $V_{out} = V_0[1 + \xi(t / mT)]$, $|\xi| << 1$, $0 \le t \le mT$ where mT is the burst length, an acceptable clock jitter $\delta t_{clk} / T$ in a full aperture BPM is

$$\delta t_{clk} / T \le (\alpha_1 / 2^n)(2A / |V_0|)(m / |\xi|) \quad (8)$$

where $\pm A$ is the ADC voltage range. For $|V_0| \approx A$, $\alpha_1 = 1$, $n = 16$, $m = 3$ and $|\xi| = 0.1$, $\delta t_{clk} / T \le 1 \cdot 10^{-3}$. With $\delta t_{clk} / T = 1 \cdot 10^{-3}$, the coefficient $\alpha_2 = \sqrt{2}$.

For a cupola-like top and with a sample moment at its apex, the voltage noise generated by the ADC clock jitter is a non-linear transformation of the latter and has features analogous to the features mentioned above for synchronous detector reference jitter.

IV. To reduce the contribution of the additional voltage noise components generated in the detector and the ADC (and contribution of the buffer amplifier noise as well) and to come closer to the BPM resolution lower limit, a common measure is to increase the difference channel amplifier gain: $G_{As} = G,\ G_{Ad} = KG,\quad K >> 1$. Assume that in the BPM $g_d = g_s$. Using the signals at the amplifier outputs, the beam position Y can be written as

$$Y = (R_{eff} / K)(V_{Ad} / V_{As}) \tag{9}$$

Assume that the input voltage ranges of the detectors in both channels are equal which can be written as $V_{Ad}|_{max} = V_{As}|_{max}$. In this case the range Y_{max} of beam offsets shrinks K times with regards to a full aperture BPM: $Y_{max} = R_{eff} / K$. Using (3), the resolution can be written as

$$\sqrt{<y^2>}|_A = R_{eff}\frac{1}{K}\cdot\frac{K\sqrt{<u^2>}}{\bar{V}_{As}}\sqrt{F_{Ad} + F_{As}\left(\frac{\bar{Y}}{R_{eff}}\right)^2} \tag{10}$$

With $Y_{max} = R_{eff} / K$ and $F_{As} \approx F_{Ad}$ the second term under the square root can be neglected. The thermal noise magnitude at the detector input is K times increased, which is equivalent to having contribution of the noise in the following circuits reduced by the same factor.

BEAM-BASED RESOLUTION TEST

Using the expressions (3), (6) and (10), the BPM resolution can be re-written as

$$\sqrt{<y^2>}|_{out} = R_{eff}\frac{1}{K}\cdot\frac{K\sqrt{<u^2>}}{\bar{V}_{out\,s} / G_{s\,tot}}\sqrt{F_{d\,tot}} \tag{11}$$

During resolution measurements, the strip line pickup signals were attenuated by 7dB. That was equivalent to a virtual decrease of the run beam intensity by up to 0.3nC. The BPM output was $|V_{out\,s}| \approx A = 1\text{V}$. So, $G_{s\,tot} = 1\text{V}/[(0.7\text{V}/1\text{nC})\cdot 0.3\text{nC}] \approx 4.8$. For $R_{eff} = 9\text{mm}$, $F_{d\,tot} = 2.5$ and $G_{s\,tot} = 5$ the expression (11) yields $\sqrt{<y^2>}|_{out} \approx 0.55\mu\text{m}$. The BPM range becomes $\tilde{\mathfrak{R}} = (-84)\text{dB}$.

The BPM output signals were measured with a 2GHz 14bit ±1V recorder GFT6004 (from Acquitek). For $|V_{out\,s}| \approx A = 1\text{V}$ its effective resolution is $R = 1/13\text{bit} = -78\text{dB}$. With $K = 14\text{dB}$ the resolution enhances to $(-92)\text{dB}$ which exceeds $\tilde{\mathfrak{R}}$ by 8dB. However, whilst data processing, it was discovered that the recorder had an additional noise component, which increases with larger input voltages (see array 9 in Table 2 below).

The recorder was free-running and got stopped (with some delay) at each shot by the BPM sum signal. As its clock was unsynchronised with beam, the BPM pulse magnitude at each shot was calculated as a maximum of a polynomial interpolation curve constructed on a maximum sample and two adjacent samples.

In the first test run, a single BPM was used. Its inputs were fed with signals taken from one pickup strip line. In the second run (three months later), two BPMs were used connected in parallel to a single pickup. For the first run a position reading std across a shot array gave the BPM resolution. For the second run, the BPM resolution was calculated as a divided by $\sqrt{2}$ std across a position difference array obtained from the readings of the two BPMs.

The first run std values for effective pickup aperture 1/3 of $R_{eff} = 9\text{mm}$ (K =10dB) are given in Table 1. Table 2 is for 1/5 of R_{eff} (K =14dB), arrays 6 to 8 are from the first run, and array 9 is from the second run.

Table 1

array	1	2	3	4	5
std, μm	3.8	1.3	1.8	1.5	1.6

Table 2

array	6	7	8	9
std, μm	1.0	0.8	1.1	1.4

CONCLUSIONS

For an electron bunch intensity of 0.3nC, in a test at the ATF, a single shot strip line BPM resolution of about 1μm has been achieved, for an effective pickup aperture of up to 1/5.

For further BPM resolution investigation, it is necessary to equip the BPM with its own ADCs.

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