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ANALYSIS OF THE CALIBRATION REQUIREMENTS FOR THE BOOSTER BEAM POSITION MONITORING SYSTEM

D. J. Ciardullo

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Collider Accelerator Department

Brookhaven National Laboratory

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DOMINIC J. CIARDULLO

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ACCELERATOR DEVELOPMENT DEPARTMENT
BROOKHAVEN NATIONAL LABORATORY
UPTON, NEW YORK 11973

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Introduction:

The purpose of the calibration mode for the Booster Beam Position Monitoring (BPM) system is to:

1. provide a method for correcting any position measurement errors due to

   . mechanical asymmetries in the detector and

   . gain and/or offsets in the processing electronics

2. provide a means whereby the operator can (from the control room) establish confidence as to the current operating condition of each PUE station.

Measurements made on each detector prior to its installation in the Booster will provide the basic equation relating the front end electronics output to the actual beam position at a particular PUE station:

$$\text{Position} = M \frac{(V_A - V_B)}{(V_A + V_B)} + P \qquad [1]$$

where:

"M" has been measured to be on the order of 100 mm and is particular to a given detector (actual prototype value is approximately 93 mm)

"V_A" and "V_B" are the voltages on the pickup electrodes.

In the above equation, "P" is the apparent position offset (in mm) which results from the PUE having different electrical and mechanical centers (i.e., mechanical asymmetries within the detector).

The value for P does not account for any offsets or unequal gains in the BPM front end electronics: thus the voltages V_A and V_B must be corrected for this previous to its insertion into equation [1]. This paper will primarily focus on how the apparent beam position offset due to the BPM electronics can be minimized by correcting V_A and V_B with constants obtained during a calibration routine.

Since we wish to obtain a position precision of 0.1 mm, we need approximately 0.1 % resolution, or 60 dB of isolation between the two input channels at the "front end" of the processing electronics (ie, up until both the sum and difference of the two input signals is acquired and digitized). This calculation is based upon measurements made on the prototype electrostatic PUEs for the Booster. Using equation [1], and assuming a perfect detector (i.e., P=0), then for 0.1 mm position resolution, we require:

$$0.1 \text{ mm} = 100 \text{ mm} \times \frac{(V_A - V_B)}{(V_A + V_B)} \qquad [2]$$

$$\frac{(V_A - V_B)}{(V_A + V_B)} = 0.001 \quad \text{---->} \quad -60 \text{ dB} \qquad [3]$$

Although the processing electronics is aligned to achieve 60 dB isolation (between outputs) previous to its installation in the Booster, a method is needed to account for any gain changes which might occur over time.

Assumptions:

The following assumptions and approximations are made to simplify this evaluation:

1. The system ADCs have sufficient resolution for their errors not to enter into the analysis.

2. The calibration ring maintains its original coupling profile to each pickup electrode for the duration of its lifetime.

3. Since the coupling from the calibration ring to each pickup electrode is identical to within better than -60 dB, we can assume it to act as an ideal voltage divider (i.e., equal voltages appear on each plate).

Calibration results will depend upon both the gain setting of the electronics, as well as the number of turns which are integrated over during a particular machine cycle.

The Calibration Signal:

The calibration signal originates from a dedicated square wave oscillator within the BPM electronics. It is applied to the detector's calibration ring and split into two equal voltages, each of magnitude $V_C G_C$, where V_C is the calibration voltage at each pickup electrode (not necessarily a known value) and G_C is the coupling constant of the calibration ring. Obtaining the calibration signal through the detector provides confidence that all of the coaxial signal cables between it and the electronics are connected. The calibration ring also eliminates the need for a precision splitter and matched cables within the calibration section of the BPM electronics.

Basic Strategy:

The analysis of the BPM system calibration will be developed as follows:

- First, it is shown that the gains and offsets of components located in each of the two legs which immediately follow the hybrid (i.e., the sum leg and the difference leg) can be combined.

- Then, while manipulating a calibration signal at the input to the BPM electronics, the sum and difference voltages measured by the system ADCs can be used to obtain expressions for intermediate gain constants.

- These constants can then be used to realize expressions for the voltages which appear at the pickup plates (with reference to the calibration voltage).

- The equations developed up to this point take voltages which can be readily measured by the system and relate them to the voltages at each plate, normalized to the calibration signal. Once the plate voltages are known, it is a simple matter to compute the difference/sum ratio. Upon calculation of this ratio, all reference to the calibration signal vanishes.

- We now have a diff/sum ratio which is corrected for the electronics associated with a particular PUE station. We need only to insert this value into equation [1] to obtain the fully corrected beam position (i.e., corrected for both the electronics and the detector).

Evaluation of Calibration Requirements:

Figure 1A is a block diagram of the analog portion of the Booster BPM electronics, from the detector to the input of the ADCs. There are two items of interest in this diagram which serve to simplify the analysis. First, it should be noted that any losses in the cables which connect the PUEs with the electronics have been absorbed into the front end gains, G_A and G_B. Second, there are no DC offsets to the left of the sum and difference block, as a result of the front end amplifiers being capacitively coupled to the hybrid.

Combine gains and offsets past hybrid:

We wish to show that the gains and offsets associated with both the Base Line Restorer (BLR) and the Integrator can be lumped together into one gain and one offset (refer to Figure 1A). Define:

O_b = BLR offset	O_i = Integrator offset	V_s = signal from the hybrid SUM port
G_b = BLR gain	G_i = Integrator gain	V_d = signal from the hybrid DIFF port

The following equation relates the SUM port of the hybrid to the input of its A/D converter [$(ADC)_{sum}$]:

$$V_{SUM} = [(V_s + O_b)G_b + O_i]G_i = V_sG_bG_i + O_bG_bG_i + O_iG_i \qquad [4]$$

It should be noted that for a given gain setting and number of bunches, all of the offsets and gains associated with both the BLR and the integrator are constant. Therefore,

$$G_{sum} = G_bG_i \quad \text{and} \quad O_{sum} = O_bG_bG_i + O_iG_i \qquad [5]$$

are constants, and V_{SUM}, the input voltage to $(ADC)_{sum}$, can be represented by:

$$V_{SUM} = V_sG_{sum} + O_{sum}. \qquad [6]$$

Similarly, the equation which relates the DIFF port of the hybrid to the input of $(ADC)_{diff}$ is:

$$V_{DIFF} = [(V_d + O_{b'})G_{b'} + O_{i'}]G_{i'}$$

$$= V_dG_{b'}G_{i'} + O_{b'}G_{b'}G_{i'} + O_{i'}G_{i'} \qquad [7]$$

where the primed (´) subscripts are used to indicate the BLR-integrator pair in front of $(ADC)_{diff}$.

As before, for a given gain setting and number of bunches,

$$G_{diff} = G_{b'}G_{i'} \quad \text{and} \quad O_{diff} = O_{b'}G_{b'}G_{i'} + O_{i'}G_{i'} \qquad [8]$$

are constants, and the input voltage to $(ADC)_{diff}$ can be represented by:

$$V_{DIFF} = V_dG_{diff} + O_{diff}. \qquad [9]$$

Since the validity of combining the gains and offsets of both the BLR and the integrator has been established, the expressions relating the signals at the input of the BPM electronics to those at $(ADC)_{sum}$ and $(ADC)_{diff}$ are as follows (refer to Figure 1B):

$$V_{SUM} = V_s G_{sum} + O_{sum} = (V_A G_A + V_B G_B) G_{sum} + O_{sum} \qquad [10]$$

$$V_{DIFF} = V_d G_{diff} + O_{diff} = (V_A G_A - V_B G_B) G_{diff} + O_{diff} \qquad [11]$$

where: V_A and V_B are the two PUE plate voltages

V_s and V_d are the output voltages from the sum and difference ports of the hybrid, respectively, and

G_{sum}, G_{diff} are the values defined in [5] and [8]

O_{sum}, O_{diff}

Obtain intermediate gain constants:

It is desired to be able to determine the diff/sum ratio of the plate voltages, corrected for any gains or offsets due to the electronics. Since it is not possible to explicitly acquire all of the gains needed to calculate the voltages at each pickup, it is necessary to work with intermediate constants which can be readily measured by the system. These constants are obtained while manipulating a calibration signal at the input to the BPM electronics.

Equations [10] and [11] are the general expressions relating the gains and offsets within the BPM electronics to the voltages actually appearing at the sum and difference ADCs, respectively (refer also to Figure 1B). Since these are the only voltages which are accessible to the BPM controller (via the system ADCs), several readings must be taken during a cal sequence in order to obtain sufficient information to calibrate the electronics. The required readings will be divided into three separate cases:

1. $V_A = V_B = 0$
2. $V_A = V_c G_c$ and $V_B = 0$
3. $V_A = 0$ and $V_B = V_c G_c$

where $V_c G_c$ is the calibration signal appearing at each pickup electrode.

Case 1. $V_A = V_B = 0$:

During this portion of the calibration sequence, the gain of each channel of the BPM electronics is set to zero. Setting V_A and V_B to zero in [10] and [11] gives:

$$V_{SUM} = O_{sum} \qquad [12]$$

$$V_{DIFF} = O_{diff} \qquad [13]$$

and the offsets for both the sum and diff legs in Figure 1B are the voltages measured by each respective ADC.

Case 2. $V_A = V_cG_c$ and $V_B = 0$:

With the calibration signal at input A and no signal at input B, equations [10] and [11] become:

$$V_cG_cG_AG_{sum} = (V_{SUM\_A} - O_{sum}) \qquad [14]$$

$$V_cG_cG_AG_{diff} = (V_{DIFF\_A} - O_{diff}) \qquad [15]$$

where V_{SUM_A} and V_{DIFF_A} are the voltages at the ADCs when $V_A = V_cG_c$ and $V_B = 0$.

Note that each term on the right side of equations [14] and [15] is known. We now define a new pair of variables, each of which represents the result of the subtraction of two measured values:

$$V_{scA} = V_{SUM\_A} - O_{sum} \qquad [16]$$

$$V_{dcA} = V_{DIFF\_A} - O_{diff} \qquad [17]$$

Case 3. $V_A = 0$ and $V_B = V_cG_c$:

With the calibration signal at input B and no signal at input A, equations [10] and [11] become:

$$V_cG_cG_BG_{sum} = (V_{SUM\_B} - O_{sum}) \qquad [18]$$

$$V_cG_cG_BG_{diff} = (V_{DIFF\_B} - O_{diff}) \qquad [19]$$

where V_{SUM_B} and V_{DIFF_B} are the voltages at the ADCs when $V_A = 0$ and $V_B = V_cG_c$.

As in case 2 above, we define:

$$V_{scB} = V_{SUM\_B} - O_{sum} \qquad [20]$$

$$V_{dcB} = V_{DIFF\_B} - O_{diff} \qquad [21]$$

A set of calibration constants consisting of V_{scA}, V_{dcA}, V_{scB} and V_{dcB} is required for each gain setting of the BPM electronics used during a particular machine cycle. Modifying the number of integrating turns (N) will also require a new set of constants. One should note however, that since the integrator offset is directly proportional to the number of turns, each set of calibration constants (for different values of N) is linearly related. Therefore, for a given gain setting, two sets of calibration constants are sufficient to calculate the correction for any other number of turns.

Obtain expressions for PUE voltages:

Equations [16], [17], [20] and [21] can be used to realize expressions for the voltages at each plate, normalized to the calibration signal. Multiplying both sides of equations [10] and [11] by V_cG_c and rearranging terms gives the following:

$$V_cG_c(\mathbf{V_{SUM}} - O_{sum}) = \mathbf{V_A}V_cG_cG_AG_{sum} + \mathbf{V_B}V_cG_cG_BG_{sum} \qquad [22]$$

$$V_cG_c(\mathbf{V_{DIFF}} - O_{diff}) = \mathbf{V_A}V_cG_cG_AG_{diff} - \mathbf{V_B}V_cG_cG_BG_{diff} \qquad [23]$$

where boldface type is used to distinguish between variables during actual operation and the calibration "constants" (ie. with respect to a particular machine cycle). Substituting equations [16] and [20] into [22], and equations [17] and [21] into [23]:

$$V_cG_c(\mathbf{V_{SUM}} - O_{sum}) = \mathbf{V_A}V_{scA} + \mathbf{V_B}V_{scB} \qquad [24]$$

$$V_cG_c(\mathbf{V_{DIFF}} - O_{diff}) = \mathbf{V_A}V_{dcA} - \mathbf{V_B}V_{dcB} \qquad [25]$$

Equations [24] and [25] can now be solved simultaneously for $\mathbf{V_A}$ and $\mathbf{V_B}$, normalized to the calibration signal:

$$\frac{\mathbf{V_A}}{V_cG_c} = \frac{(\mathbf{V_{SUM}} - O_{sum})(V_{dcB}) + (\mathbf{V_{DIFF}} - O_{diff})(V_{scB})}{[V_{scA}V_{dcB} + V_{dcA}V_{scB}]} \qquad [26]$$

$$\frac{\mathbf{V_B}}{V_cG_c} = \frac{(\mathbf{V_{SUM}} - O_{sum})(V_{dcA}) - (\mathbf{V_{DIFF}} - O_{diff})(V_{scA})}{[V_{scA}V_{dcB} + V_{dcA}V_{scB}]} \qquad [27]$$

It is now possible to write expressions for both the corrected difference and the corrected sum of the two plate voltages. The resulting expressions are:

$$\frac{V_A - V_B}{V_c G_c} = \frac{(\mathbf{V_{SUM}} - O_{sum})(V_{dcB} - V_{dcA}) + (\mathbf{V_{DIFF}} - O_{diff})(V_{scB} + V_{scA})}{[V_{scA}V_{dcB} + V_{scB}V_{dcA}]} \qquad [28]$$

$$\frac{V_A + V_B}{V_c G_c} = \frac{(\mathbf{V_{SUM}} - O_{sum})(V_{dcB} + V_{dcA}) + (\mathbf{V_{DIFF}} - O_{diff})(V_{scB} - V_{scA})}{[V_{scA}V_{dcB} + V_{scB}V_{dcA}]} \qquad [29]$$

Performing the ratio of eq.[28] to eq.[29] eliminates any dependance on the calibration signal, and yields the following equation:

$$\boxed{\frac{DIFF}{SUM} = \frac{(\mathbf{V_{SUM}} - O_{sum})(V_{dcB} - V_{dcA}) + (\mathbf{V_{DIFF}} - O_{diff})(V_{scB} + V_{scA})}{(\mathbf{V_{SUM}} - O_{sum})(V_{dcB} + V_{dcA}) + (\mathbf{V_{DIFF}} - O_{diff})(V_{scB} - V_{scA})}} \qquad [30]$$

<u>**Conclusion:**</u>

It is desired to have some method of calibrating the Booster BPM system so that a high level of confidence in its measurement accuracy can be maintained after its initial installation. Analysis indicates that a calibration routine can be performed which provides sufficient information to compensate for long term active component drift within the BPM electronics. This information, when combined with a knowledge of the detector offset, can be used to determine the absolute position of the beam.

Equation [30] provides a numerical value which can be inserted into [1] to obtain the actual position of the beam, corrected for apparent offsets due to both the detector and the electronics. Constants obtained through a calibration routine operate on the SUM and DIFF voltages retrieved by the BPM system during machine operation (boldface type).

<u>**Acknowledgement:**</u>

The help of Vincent Stanziani in the development of these calibration requirements is greatly appreciated. Many of his ideas and circuit modifications were instrumental in minimizing the amount of hardware required to achieve our calibration goals.

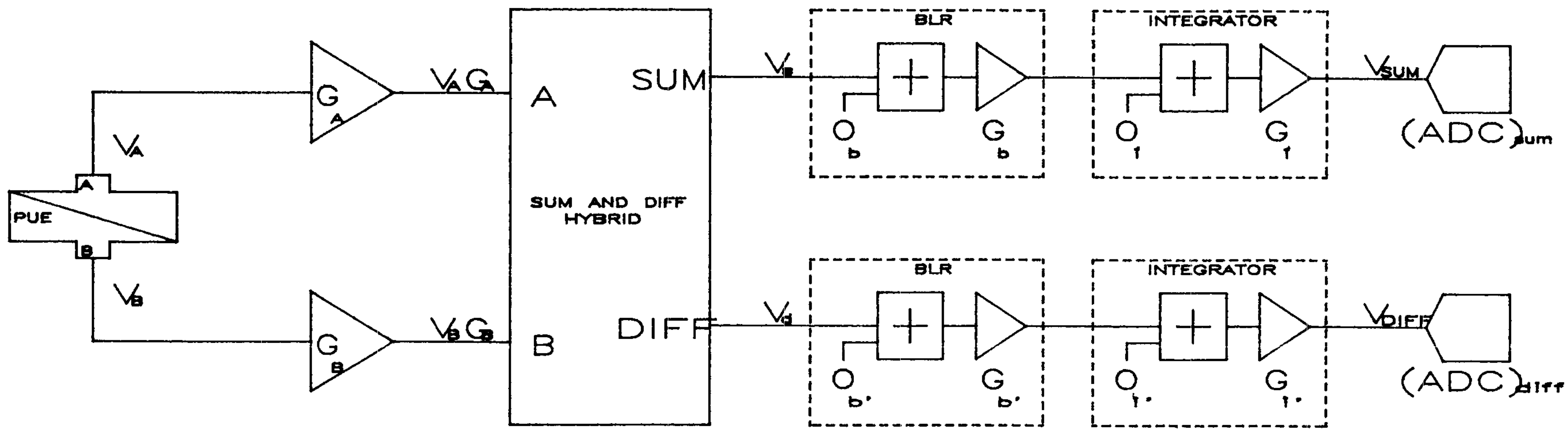

FIGURE 1A. BLOCK DIAGRAM OF BPM PROCESSING ELECTRONICS FRONT END

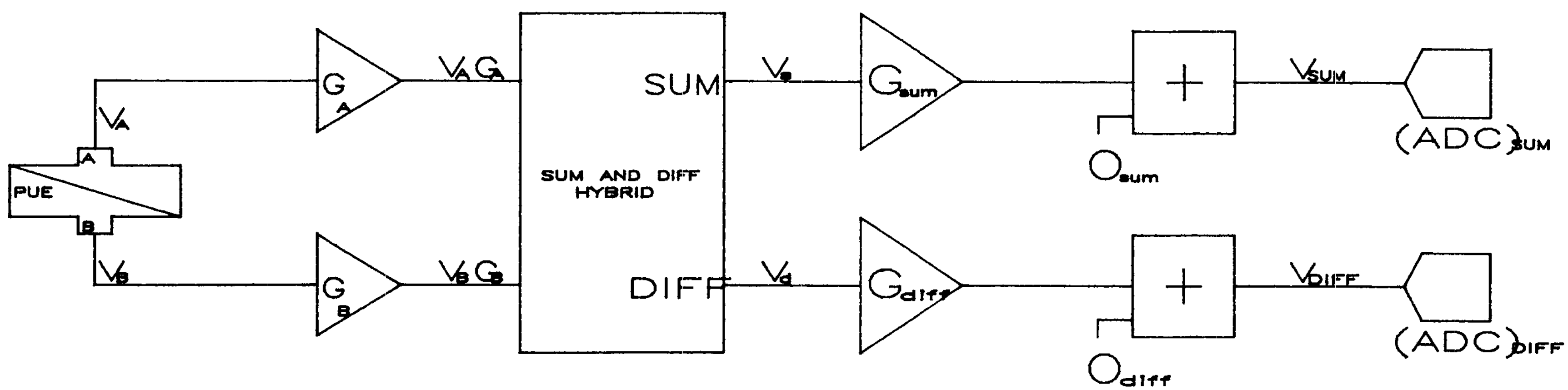

FIGURE 1B. EQUIVALENT LUMPED GAINS AND OFFSETS