# ON THE CALIBRATION MEASUREMENT OF STRIPLINE BEAM POSITION MONITOR FOR THE ELI-NP FACILITY

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## *Abstract*

Stripline Beam Position Monitor (BPM) will be installed in the Compton Gamma Source in construction at the ELI Nuclear Physics facility in Romania. A test bench for the calibration of BPM has been built to characterize the device with stretched wire measurement in order to get the BPM response map. A full S-parameters characterization is performed as well to measure the electrical offset with the "Lambertson method". This paper discusses the extensive simulations performed with full 3D electromagnetic CAD codes of the above measurements to investigate measurement accuracy, possible measurement artefacts and beam position reconstruction.

## INTRODUCTION

The BPM is used to measure the center of mass of the particle beam that travels in the vacuum chamber of an accelerator from the electromagnetic field generated by the beam. It requires an appropriate calibration in order to reconstruct accurately the beam position from the electric signals at the electrodes.

In this paper we will first describe a model of the stripline BPM which will be installed in the Compton Gamma Source at ELI-NP facility, named the Gamma Beam System (GBS) [1]. Construction tolerances result in an offset different from zero between mechanical and electrical centre of BPM; thus calibration is necessary to measure such an offset to reconstruct accurately the beam position. We consider the calibration of BPM with the Lambertson method and the wire method [2]; our results confirm the validity of the GBS BPM calibration test-bench proposed in Ref. [2].

## MODEL OF GBS STRIPLINE BPM

The GBS stripline BPM [3] is a device in which electrodes that detect the beam field are short circuited striplines, acting as a directional coupler. Figure 1 shows the HFSS-ANSYS BPM model [4].

From the analogy with a stripline directional coupler properly ended, we obtained the following S-parameters of the BPM:

$$S_{21} = \frac{j\frac{Z_C}{(Z_O+Z_E)}}{\sin(2\beta l)-j\frac{Z_C}{(Z_O+Z_E)}[1-sin^2(\beta l)]}\ , \tag{1}$$

$$S_{31} = \frac{jZ_C\frac{(Z_O-Z_E)}{(Z_O+Z_E)}}{\mathrm{j}Z_C\sin(2\beta l)+2\frac{Z_C^2}{(Z_O+Z_E)}-2sin^2(\beta l)\frac{Z_C^2+Z_OZ_E}{(Z_O+Z_E)}}\sin(2\beta l)\ , \tag{2}$$

where $\beta$ is the propagation constant, $Z_O$ and $Z_E$ are respectively the characteristic impedance of odd mode and even mode, $Z_C$ is the characteristic impedance of stripline and $l$ is the length of the stripline.

Equations 1-2 agree with the HFSS simulation results reported in Fig. 2 as well as typical measurement of BPM prototypes. The notch depends only from the longitudinal dimension of the stripline and not from the transverse configuration of the field.

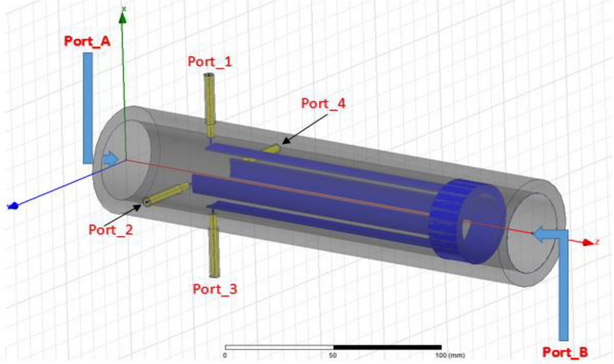

Figure 1: HFSS model of GBS stripline BPM.

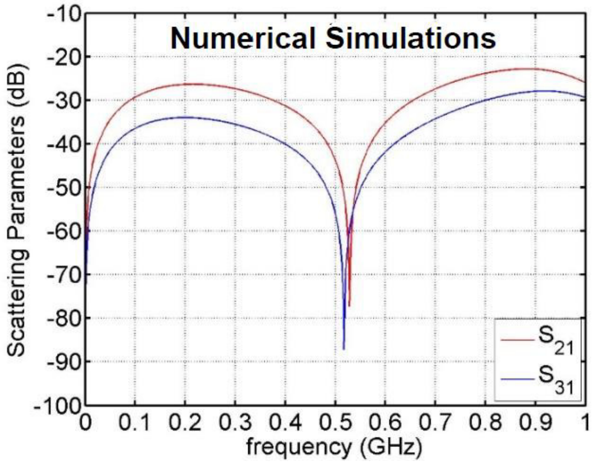

Figure 2: Transmission S-parameters versus frequency for adjacent striplines ($S_{21}$) and for opposite striplines ($S_{31}$).

The sensitivity $S$ of the BPM depends on geometrical characteristics of BPM too [3]:

$$S_{x,y} = \frac{2}{R_{M_{x,y}}}\frac{sin\frac{\phi x,y}{2}}{\frac{\phi x,y}{2}}\ , \qquad \left[\frac{1}{mm}\right] \tag{3}$$

$\phi_x$ ($\phi_y$) is the opening angle of electrodes along $x$ ($y$) direction and $R_{M_{x,y}}$ is a "corrected radius" giving a better estimate of sensitivity, according to numerical results.

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$$R_{M_{x,y}} = r_i \left(1 + \frac{2 * \phi_{x,y}}{\pi} - \frac{r_i * 2 * \phi_{x,y}}{r_{pipe} * \pi}\right), \qquad [mm] \tag{4}$$

$r_i$ being the inner radius of stripline and $r_{pipe}$ being the inner radius of BPM pipe. Equation 4 agrees with Ref. [3] when the stripline electrodes are located flush with pipe, but it gives a *S* closer to simualtion otherwise (Figure 3).

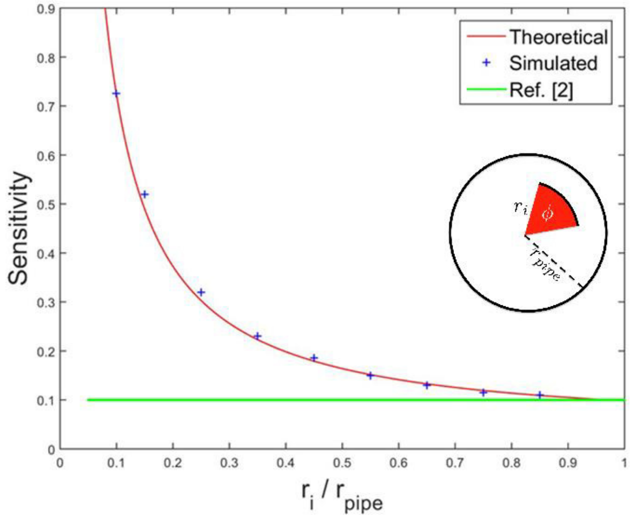

Figure 3: Sensitivity versus stripline radius $r_i$ for a given azimuthal aperture of stripline $\phi$ and pipe radius $r_{pipe}$.

## LAMBERTSON METHOD

Lambertson method [5] allows to estimate the offset measuring S-parameters at the BPM ports without the presence of a particle beam or a signal that simulate its presence (see Fig. 1). Figure 4 shows the BPM offset due to mechanical asymmetries; $t_{strip}$ ($w_{strip}$) is the thickness (width) of the strip and $d_{strip\text{-}pipe}$ the distance between the strip and the beam pipe.

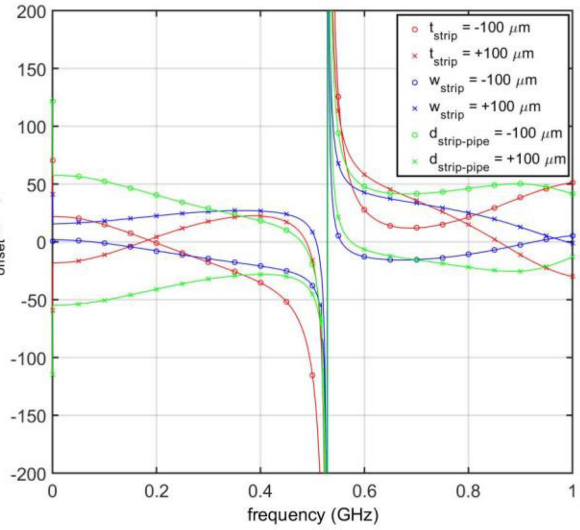

Figure 4: Frequency behaviour of $X_{offset}$ calculated with Lambertson method for all examined geometrical cases.

In presence of asymmetries on stripline the offset becomes non-linear function of the frequency also we note that tolerances of the thickness of stripline and their distance from the BPM pipe affect mostly the BPM offset. However staying within mechanical tolerances the offset is of the order of tens of microns. At the notches of S-parameters (see Figure 2), the offset presents singularities (since the Lambertson method is not applicable).

In BPM of GBS linac the length of striplines is $l_{strip} = 140\ mm$ to which corresponds a frequency calculated with the mathematical model equal to $f_{1^o\,notch} = 535\ MHz$. Simulations instead show $f_{1^o\,notch} = 527\ MHz$ where difference between the simulated value and the theoretical value is to be attributed to the terminal part of the BPM which plays the role of reactive load, i.e. tuning the notch frequency. As shown from Figure 4, the singularity (i.e. the notch of S-parameters) depends only from the longitudinal geometries of the structures (i.e. from the length of the BPM) and not depends on the transverse configuration of the file.

## WIRE METHOD

In wire method the presence of particle beam within the BPM is simulated exciting a TEM electromagnetic field by means of a properly powered thin metal wire. The wire is coaxial to BPM and scanning the BPM transverse plane. In each position in which the wire is positioned from time to time the signals from the BPM electrodes are measured.

By means of HFSS simulations we evaluated the systematic effects in the BPM calibration due any mismatch between wire signal and BPM at interface ports between vacuum chamber and device (see $Port_A$ and $Port_B$ of Figure 1), the misalignment between the wire and BPM axis, as well as the finite cross section of wire.

From the signals at the BPM electrodes one can estimate the position of the wire within the BPM. This reconstruction is then compared with the actual position of the wire, as given by an accurate positioning tools. To reconstruct the wire position from the signals collected by the four electrodes of the BPM we use two quantities, indicated with *X* and *Y*, and defined by the potentials on the electrodes themselves (Fig.1):

$$X = \frac{\Delta V_x}{\sum V_x} = \frac{V_{Port_1} - V_{Port_3}}{V_{Port_1} + V_{Port_3}}, Y = \frac{\Delta V_y}{\sum V_y} = \frac{V_{Port_2} - V_{Port_4}}{V_{Port_2} + V_{Port_4}}, \tag{5}$$

where and $\Delta V_{x,y}$ is respectively the potential difference between the couple of stripline electrodes along x and y direction and $\sum V_{x,y}$ is respectively the potential sum of the potentials on the stripline electrodes along x and y direction.

Because of nonlinear behavior of BPM we need additional correction, depending on the application, that involve quantities defined in Eq. (5), and that allows us to reconstruct the actual position of the wire from measured signals.

In particular, we used the least squares method for the position reconstruction. If $e(X, Y)$ is the estimated beam position, $p_{mn}$ are coefficients calculated minimising the difference between actual and estimated position of wire; we have then:

$$e(X,Y)=\sum_{m=0}^{M}\sum_{n=0}^{M-m}p_{mn}\,(X)^m(Y)^n, \qquad (6)$$

Using for $e(X,Y)$ a first order polynomial ($M=1$), the nonlinear behavior of the reconstructed position is clear from Fig. 5; thus only in a neighborhood of the origin the BPM measure will be accurate. The accuracy can be defined as the absolute value of the distance between actual and rebuilt position of the wire for each position.

In the GBS linac, the beam will travel at the centre of the BPM and thus M=1 will be enough; $p_{11}$ is actually the sensitivity *S*. Using higher order polynomials, we get a better accuracy on a wider area of the BPM. For instance, with $M=5$ we get an accurate reconstruction on entire internal area of the BPM (Fig.6). Such a reconstruction is mandatory when the beam trajecotry is far from the center.

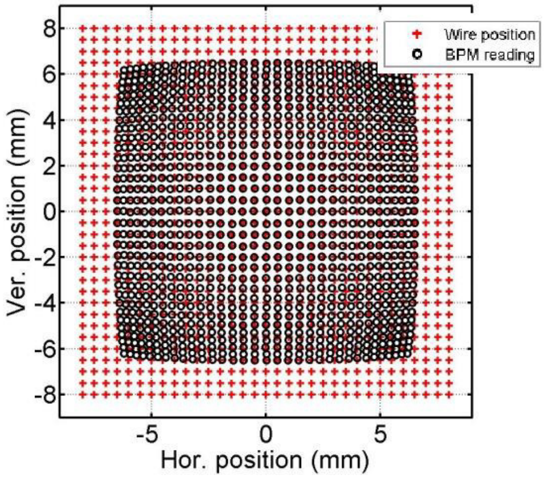

Figure 5: Position map comparing the wire position and the BPM reading ($M=1$).

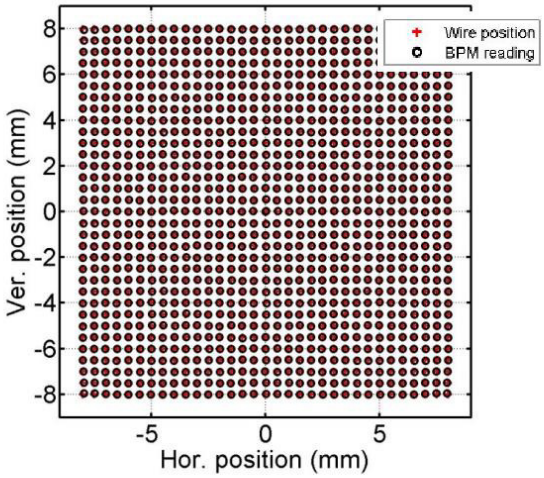

Figure 6: Position map comparing the wire position and the BPM reading ($M=5$).

Our (extensive) numerical analysis confirms that RF mismatches between wire signal and BPM (at $Port_A$ and $Port_B$ from Figure 1) do not alter the result of position reconstruction. Some (small) effect may be given from a poor alignment of the wire; such aspect is usally very well controlled in test-benches as shown in Ref. [2].

## SUMMARY

We performed numerical simulations on the ELI GBS BPM reproducing the expected BPM S-parameters; we have proposed a more accurate formula for the BPM sensitivity. We also highlighted that asymmetries on stripline results in a tens of $\mu$m offset (calculated by Lambertson method) varying with the frequency. Finally we found that the possible causes of systematic effects that can affect the calibration performed with wire method (used also in [2]) do not alter the reconstruction of wire position (made with least squares method for example).

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