CAVITY BPM DESIGN, SIMULATIONS AND TESTING FOR THE FERMI@ELETTRA PROJECT*

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Abstract

The cavity Beam Position Monitor (BPM) is a fundamental beam diagnostic instrument for a seeded FEL, like FERMI@Elettra. It allows the measurements of the electron beam trajectory in a non-destructive way and with sub-micron resolution. The high resolution cavity BPM is providing relies on the excitation of the dipole mode that is originated when the bunch passes off axis in the cavity. In this paper we present the prototype of cavity BPM developed for the FERMI@Elettra facility. The RF parameters of the cavities have been determined by means of Ansoft HFSS while using the CST Particle Studio the level of the output signals from the cavities have been also estimated. Furthermore, the design of the prototype electronics for the acquisition and codnitioning of the signals from the BPM cavities is presented as well. The prototype has been installed in the FERMI Linac during the last commissioning phase and preliminary results with the electron beam are also presented.

INTRODUCTION

The Cavity BPM is used in the FERMI@Elettra [1] project to determine the electron beam transversal position within a μm target resolution in single shot. A new prototype has been designed and simulated in the FERMI@Elettra laboratories. Some preliminary characterization were performed at the workbench to test the C-BPM before its installation in the undulator area. The aim of our work is to compare the simulated HFSS [2] and CST [3] results, with both the experimental workbench measurements and the electron beam test. The parameters of interest are, for both the reference and the BPM cavities, the resonant frequencies, the internal and external Q, the (R/Q) value, the β coupling factor, the loss factor and the level of the output signals. Moreover, the cross-talk of the orthogonal polarizations has also been measured with the network analyzer.

This paper proposes a new electronic system instead of the IQ demodulation. There are two versions of this circuit. One version works with a negligible electron beam tilt signal, the other gives the right value of the electron beam offset rejecting the disturbing component of the electron beam tilt signal, thus performing the measurement also when the tilt signal is not negligible. This new approach in the BPM signal processing is easier to realize, gives the maximum amount of signal when the electron beam is travelling through the cavity centre. Moreover the first stage of the electronics is made only with passive and linear electronic components so that noise and non linearity are not introduced in the first electronic stage.

The paper conludes with the in-tunnel test of the Cavity BPM.

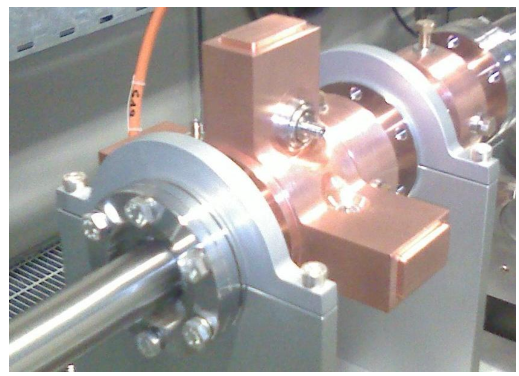

Figure 1: Photo of the Cavity BPM

SIMULATIONS

This section focuses on the simulations made with Ansoft HFSS [2] and CST Particle Studio [3]. The HFSS simulator has been used to analyze the RF parameters of the cavities, while the CST Particle Studio has been used to determine the level of the output signals from the cavities.

HFSS Simulations

The HFSS simulations have been carried on both the reference and the BPM cavity, using the "symmetry planes" with 90° symmetry, 180° symmetry, and with no symmetry planes; results are summarized in tables 1 and 2 (the shunt resistance 'R' is meant to be the circuital resistance defined from the circuit theory and not by the linac convention). The output voltage in a Z_0 matched load is calculated by the relation (1).

$$V_{OUT} = \sqrt{2Z_0 \frac{\omega}{Q_{EXT}} k_{010}}\, q \tag{1}$$

where Q_{EXT} is the external quality factor, ω is the resonant angular frequency, k_{010} is the loss factor and q is the bunch charge.

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Table 1: HFSS simulations for the reference cavity

HFSS Simulations for the reference cavity				
Symmetry planes	90° (Eigenmode)	180° (Eigenmode)	180° (Driven Modal)	No symmetries(Driven Modal)
f_{RES} (MHz)	6457	6455	6455	6457
Q_0	6314	6268	-	-
S_{11}	-	-	0.741	0.740
β	-	-	0.148	0.149
$(R/Q)_{010}$ (Ω)	36	36	-	-
k_{010} (V/nC)	731	731	-	-
Q_{EXT}	-	-	42351	42000
P_{OUT}@1nC (W)	-	-	0.70	0.71
V_{OUT}@1nC (V)	-	-	8.38	8.41
Convergence	very good	good	good	bad
# Tetrahedra	140000	47000	46000	358000

Table 2: HFSS simulations for the BPM cavity

HFSS Simulations for the BPM cavity						
Symmetry planes	90° (E.)	90° (D.)	180° (E.)	180° (D.)	None (D.)	None +ant (D.)
f_{RES} (MHz)	6483.6	6483.6	6483.6	6482.5	6485.0	6484.6
Q_0	7900	-	7882	-	-	-
S_{11}	-	0.815	-	0.910	0.900	0.900
$\beta_{PORT\,1}$	-	0.102	-	0.0471	0.0526	0.0526
$(R/Q)_{110}$ (Ω/mm^2)	0.46	-	0.46	-	-	-
k_{110} $(V/nC/mm^2)$	9.40	-	9.45	-	-	-
$Q_{EXT\,PORT\,1}$	-	78000	-	168000	150000	150000
$P_{OUT\,PORT\,1}$@1nC (W)	-	4.90e-3	-	2.28e-3	2.56e-3	2.56e-3
$V_{OUT\,PORT\,1}$@1nC (V)*	-	0.70	-	0.48	0.50	0.50
Convergence	good	good	good	average	bad	average
# Tetrahedra	23000	55000	38000	59000	285000	400000

*: We are confident on the last values of $V_{OUT\,PORT\,1} = 0.50V$
where: "E.": Eigenmode, "D.": Driven Modal, "+ant": plus antenna

CST Simulations

The CST simulator has been used to analyze the output signals from both cavities. In fact, the Particle Studio toolbox allows the simulation of the electron beam interacting with the cavities. The electron beam has been set with a charge of -1 nC and σ_Z = 6 mm. The electron beam passes through the reference cavity on the beam pipe axis. In the BPM cavity simulation the electron beam is set with 1 mm offset. Figure 2 represents the output voltage from the BPM cavity.

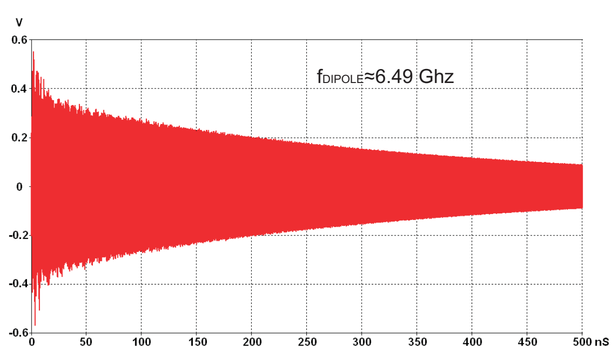

Figure 2: Output signal of the BPM Cavity.

All the CST results are summarized in table 3.

Table 3: CST output signal levels

	Ref. Cavity	**BPM Cavity**
$V_{OUT}[V](\sigma_Z = 6mm)$	7	0.40
$V_{OUT}[V](\sigma_Z < 1mm)$*	9	0.56

*: Values calculated with the form factor

THE ELECTRONIC SYSTEM

This section describes the new approach adopted for the electronics used in the FERMI@Elettra BPM cavities. The schematic of the first kind of circuit is depicted in figure 3 (the unused ports are closed on a matched-load).

The signals of the reference and of the BPM cavity go to the 180° hybrid, which gives the sum(Σ) and the difference(Δ) of such signals. When the electron beam is crossing the cavity with small offsets, the BPM signal is very weak, but both output signals from the hybrid have a strong value. In particular, with zero offset, the sum and difference have the same level. This is the first advantage of this circuit, which allows to have a strong signal even with small offsets of the electron beam.

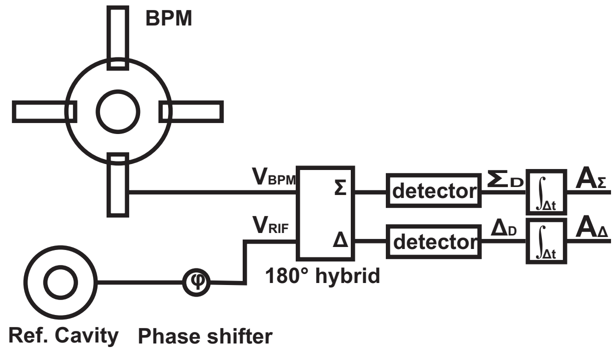

Figure 3: First type of electronic circuit.

As shown in figure 3, the circuitry follows with an active detector, and with an integrator that calculates the area of the pulse.

The hybrid input signals are:

$$V_{rif} = Acos(\omega t)e^{-t/\tau_R}$$
$$V_{bpm} = (B_\sigma cos(\omega t) + B_t sin(\omega t))e^{-t/\tau_B} \quad (2)$$

where "A" is the amplitude of the reference signal, "B_σ" is the BPM offset signal, "B_t" is BPM tilt signal, "τ_R" and "τ_B" are the reference and BPM cavity time constants, respectively. The sum and the difference output signals from the hybrid are, respectively:

$$\Sigma = (Ae^{-t/\tau_R} + B_\sigma e^{-t/\tau_B})cos(\omega t) + B_t e^{-t/\tau_B} sin(\omega t)$$

$$\Delta = (Ae^{-t/\tau_R} - B_\sigma e^{-t/\tau_B})cos(\omega t) - B_t e^{-t/\tau_B} sin(\omega t)$$

The detectors extract the amplitude of such signals, giving therefore:

$$\Sigma_D = \sqrt{(Ae^{-t/\tau_R} + B_\sigma e^{-t/\tau_B})^2 + (B_t e^{-t/\tau_B})^2}$$
$$\Delta_D = \sqrt{(Ae^{-t/\tau_R} - B_\sigma e^{-t/\tau_B})^2 + (B_t e^{-t/\tau_B})^2} \quad (3)$$

The integrators numerically calculate the area of the pulses. Such values (A_Σ and A_Δ) go to the FPGA-board [4]. The latter allows to estimate the electron beam offset. In this case the tilt signal B_t must be negligible with respect to the offset signal B_σ, because in the offset measurement the tilt component is an unwanted signal.

Rejection of the tilt signal

By using the same kind of electronics is possible to reject the tilt signal with the configuration of figure 4. The "d" signal is therefore:

$$d = \Sigma_D^2 - \Delta_D^2 = 4AB_\sigma e^{-t/\tau_R} e^{-t/\tau_B} \quad (4)$$

Hence, the integrator gives the (5)

$$A_d \propto 4AB_\sigma \quad (5)$$

This result is tilt-free and it is analogous to that obtained with the coherent demodulation.

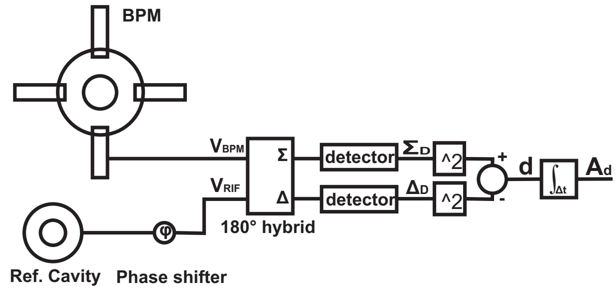

Figure 4: Second type of electronic circuit.

WORKBENCH MEASUREMENTS

This section deals with the workbench measurements. The aim is to measure the RF parameters of both the reference and the BPM cavities and to compare them with the simulated ones. Table 4 summarizes the results obtained with the vector network analyzer.

Table 4: Workbench measurements

Ref. Cavity	Cavity BPM
Mode TM_{010}	Mode TM_{110}
f_{010} = 6476 MHz	f_{110} = 6474 MHz
Q_0 = 6236	Q_0 = 7643
S_{11} = 0.86	S_{11} = 0.89
β = 0.075	β = 0.058
Q_{EXT} = 83100	$Q_{EXT\ PORT\ 1}$ = 130000
$(R/Q)_{010}$*=36 Ω/mm^2	$(R/Q)_{110}$*=0.46 Ω/mm^2
k_{010}* = 731 $V/nC/mm^2$	k_{110}* = 9.4 $V/nC/mm^2$
V_{RIF}=6V	V_{BPM}=0.54V

*: The "R" value is obtained from the HFSS simulations

The BPM RF parameters are in good agreement with those of the HFSS simulations. However, for the reference cavity, the simulated resonant frequency of table 1(last column) differs from the one of table 4 of 19 MHz. Moreover, the simulated S_{11} is slightly different from the measured one. This is due to the connector used in the reference cavity. In fact, since the antenna is floating inside the cavity, a ceramic layer has been used to stabilize it; but it affects the RF parameters as well.

Crosstalk

The crosstalk between the orthogonal ports has also been measured by measuring the scattering parameter between such ports that ideally must be isolated. The average value of crosstalk is -49 dB, which is below a threshold of -40 dB; therefore this result is very good.

ELECTRON BEAM MEASUREMENTS

This section presents the test of the reference and BPM cavity with the electron beam. The objective is to assess the level of output signals by changing the position of the electron beam. The electric charge is 270 pC, while the duration of the pulse(σ_t) is nearly 10ps. The levels of the output signals are measured by varying the offset of the electron beam. The cavity BPM is placed between two microstrip BPMs ("BPM A" and "BPM B"), as shown in figure 5.

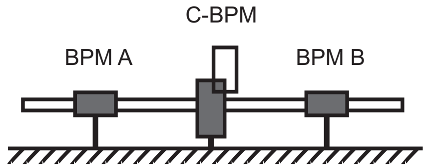

Figure 5: BPM placement

The Cavity BPM is not perfectly aligned with the BPM microstrips (see Fig. 5). For this reason the first stage in the e-beam measurements has the aim to find the electrical zero of the C-BPM. This is achieved by changing the position of the electron beam, until the minimum level of the output signals from the C-BPM is reached. When the electrical zero of the C-BPM is found, the electron beam is moved and the C-BPM output signals (Peak to peak) are recorded. Table 5 summarizes the experimental results.

Table 5: BPM Tunnel measurements

#	BPM A [mm]		BPM B [mm]		Output signals [mV]		
	x	y	x	y	Ref	x-Pos	y-Pos
1	**-1.0**	**-1.1**	**-1.0**	**-1.1**	**602**	**62**	**66**
2	1.0	-1.1	1.0	-1.1	770	405	57
3	-0.8	1.0	-0.8	1.0	570	70	360
4	0.0	1.0	0.0	1.0	625	216	346
5	0.0	0.5	0.0	0.5	629	213	275
6	0.0	0.0	0.0	0.0	608	208	204

The measurement #1 is the electrical zero of the C-BPM, in which the output signals are very weak for both the x and y ports. However, the BPM A and BPM B position are not zero. This is due to the misalignments, because the e-beam crosses the BPM A and BPM B with -1 mm offset in 'x', and -1.1 mm offset in 'y' when the C-BPM is crossed in the electric centre. The next measurements (from 2 to 6) have been made changing the offset of the e-beam and measuring the output level of the signals. The reference signal is altogether constant with a mean value of 627 mV Peak-to-peak with 270pC of bunch charge. Thus, the amplitude of the output signal with 1nC of electric charge and $\sigma_t < 5$ps would be 2.52V.

With the X offset the mean value of the X output signal is 171 mV(Pk-Pk)/mm with 270pC of bunch charge, that gives 0.33 V/mm with 1nC and $\sigma_t < 5$ps.

With the Y offset the mean value of the Y output signal is 145 mV(Pk-Pk)/mm with 270pC of bunch charge, that gives 0.30 V/mm with 1nC and $\sigma_t < 5$ps.

The tunnel measurements revealed a low output signal from the reference cavity, because it is nearly three times lower compared to the estimated one. This might be due to the connector, in fact, such connector has a ceramic component that supports the antenna, and it can cause backward power reflections. The measured BPM signal is lower, but is it very close to the estimated value.

The last step is to analyze the harmonic components of the output signal from the BPM cavity. This has been made by a basic MatLab FFT, obtaining the results of figure 6.

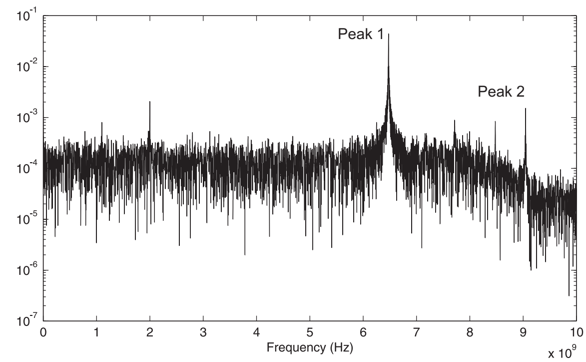

Figure 6: FFT of the BPM signal

The peak # '1' at 6.476 GHz is the dipole mode, while the peak # '2' at 9.046 GHz is the quadrupole mode (under-vacuum values).

CONCLUSION

In this paper the simulation and the test of the cavity BPM had been presented. The resonant frequency simulated with HFSS for the reference cavity is different from the real one of 19 MHz. The HFSS and CST simulations are in good agreement about the output signal levels. The electron beam measurements revealed the same order of magnitude for the BPM signal level, but the reference signal is lower than estimated by a factor of 3. This might be due to the geometry of the connectors and to the mechanical tolerances, which might produce power reflections and losses.

The new RF frontend has been also presented. Its advantage is the linearity of the first stages, which consist only of passive electronic components. This avoids the introduction of noise sources.

REFERENCES

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