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Technical Design Report of BPM Striplines of MEBT

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Change History

Rev.	Date	Author(s)	Description
0.0	2017-06-28	S. Varnasseri	First Version
1.0	2017-06-29	I. Bustinduy	Small corrections
2.0	2017-06-30	S. Varnasseri	Figures numbers edition

1. INTRODUCTION

There are overall 8 BPM pickups installed within the MEBT (Fig. 1). The primary purpose of the BPMs is the beam position and phase measurement. Furthermore, direct signals from one BPM also will be used for the MEBT beam chopper rise/fall time performance evaluation, which in this case it acts like an FCT. In addition, it is expected from the information of the BPM stripline electrode signal phases, the TOF measurement to provide information on beam energy will be evaluated.

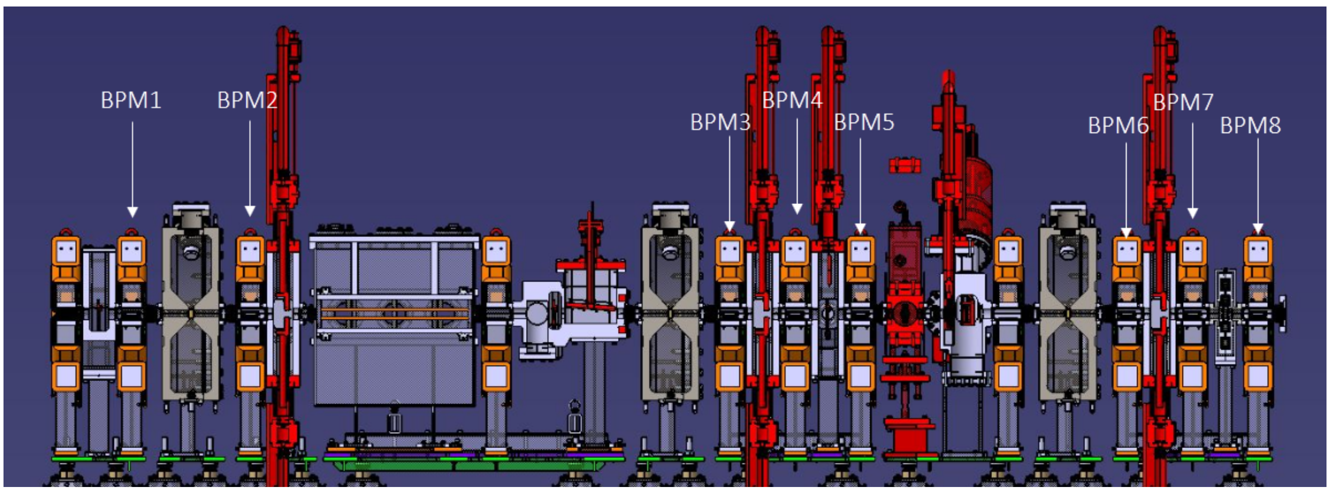

Figure 1: BPM locations in the MEBT.

All the BPMs will be installed inside quadrupoles and all quadrupole magnets, except the (Q1, Q4 and Q8) include the BPM striplines. BPM1, BPM2, BPM7 and BPM8 have more important role of providing information for the prevoius and next sections of accelerator (i.e RFQ and DTL)

2. REQUIREMENTS

Table. 1, shows the requirements of the beam position monitoring in general terms within MEBT. It shows the mechanical accuracy, positioning resolution, and beam current range in which the BPMs are expected to provide information. The values correspond to the overall BPM system which includes the BPM Striplines, coaxial cables, front-end electronics and acquisition system.

Table.1: General BPM system requirements

Reference	Definition	Explanation	Comments
MEBT-L4-PBI-170	Transverse beam position measurement: accuracy	The beam position with respect to the beam theoretical axis shall be measured with an accuracy of better than ± 200 um averaged over the beam pulse	BPM stripline contribution is ±100 um.
MEBT-L4-PBI-180	Transverse beam position measurement: resolution	The beam position shall be measured with a resolution better than 20 µm averaged over the pulse length	
MEBT-L4-PBI-190	Transverse beam position measurement: number of measurements	There shall be 8 BPMS in the MEBT	
MEBT-L4-PBI-200	Beam energy measurement: accuracy	The beam energy shall be measured with an accuracy of better than ± 10 keV averaged over the beam pulse	Scheme shall be provided. BPM SL contribution shall be defined.
MEBT-L4-PBI-210	Beam energy measurement resolution	The beam energy shall be measured with a resolution of 5 keV or better	
MEBT-L4-PBI-010	Operating domain: beam current range	All measurements in the MEBT shall be done over a beam current range from 1 mA to the nominal	

3. INTERFACES

Table. 2 shows the interfaces of the BPM Striplines with various subsystems, including mechanical and electrical parts. It shows the number and location of BPMs, BPM pipe minimum internal diameter, alignment and processing electronics. Number and locations of the BPMs have been agreed in a joint Integration workshop in March 2016 held in Bilbao.

Table. 2: MEBT BPM Striplines Interfaces

		Clarification	**Comments**
BPM number and location	The BPMs shall be installed inside quadrupoles.	8 BPM sensors shall be integrated in selected quadrupole magnets of the MEBT (i.e. Q2, Q3, Q5, Q6, Q7, Q9, Q10, Q11).	Workshop March 2016
MEBT BPM beam pipe size	the MEBT BPMs shall have beam entry/exit ports with minimum 36.8 mm diameter	Overall design of the MEBT BPMs including input/output ports shall be consistent with the MEBT mechanical integration. MEBT Schematics ESS-0053289.2	
Vacuum compatibility	all BPMs need to operate under vacuum. The BPMs shall undergo vacuum tests before installation in the linac.		
BPM alignment	The BPM center shall be aligned with the correspondent quadrupole axis with a total mechanical alignment error of less than TBD.		BBA alignment is expected
Phase-reference frequency	frequency of the phase reference signal shall be 704.42 MHz for the MEBT BPMs.		
BPM connector	BPM connector shall be determined along the QUAD-BPM combined design by Bilbao.		SMA vacuum feedthrough

4. DESIGN CONCEPTS

The design of BPM Stripline involves iterations on various electrical, material, vacuum and mechanical parameters, while having also some beam parameters variation within MEBT. As an example, the beam size has some large variations during the passage within MEBT (see Table 3). This affects the beam spectrum seen by the BPM electrodes and therefore variations in the induced voltage at a specific frequency component. The frequency of bunches is 352.2 MHz, and the front-end processing frequency is chosen as 704.4 MHz. The electromagnetic simulations including the 3D, low energy analysis and high frequency analysis have been performed with the CST studio.

4.1. BEAM PARAMETERS

The beam parameters of MEBT which are related to BPM Stripline are given in Table.3. The values correspond to the nominal values of the operation.

Table 3: BPM Related Beam Parameters

Parameter	**Value**	**Unit**
Beam energy	3.62	MeV
Beam current (avg.)	62.5	mA
Particles/bunch	1.1e9	
Readout frequency	704	MHz
RF frequency	352	MHz
Bunch length	60-180	ps
Pulse length (max.)	2.8	ms

4.2. BUNCH FREQUENCY SPECTRUM

Within MEBT, however there is no variation in beam energy, but the bunch length varies through passing from RFQ to the first cells of DTL. From Stripline point of view, variation in bunch length means variation in frequency components of the bunch. Fig. 2 shows extracted bunch frequency spectrum for various bunch lengths with nominal MEBT beam current (62.5 mA) and nominal beam energy (β=0.088).

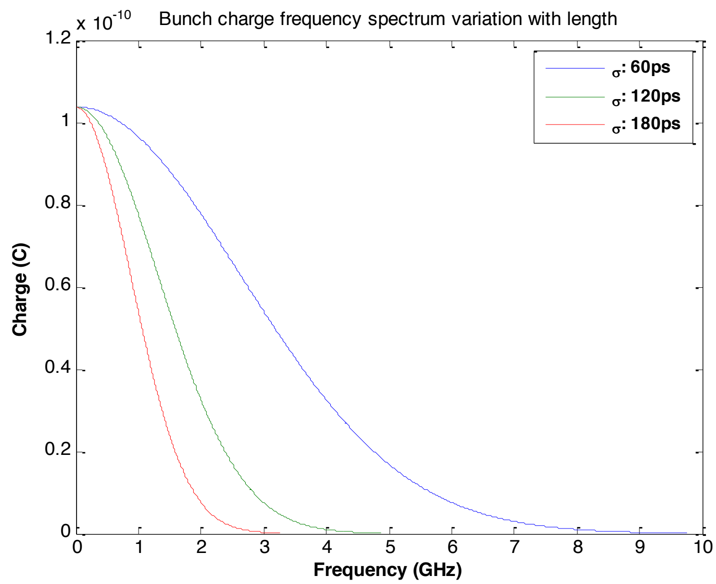

Figure 2: Bunch charge frequency spectrum variation.

4.3. MECHANICAL CONSTRAINTS

BPM Striplines are designed to be installed inside quadrupole magnets. They are supported by the magnet yokes. The quadrupole magnet yoke radial aperture is 41 mm and the horizontal/vertical aperture is 14.5mm. On the other hand, the Stripline outer diameter is 40mm and horizontal/vertical constraints are 14mm (Fig. 3).

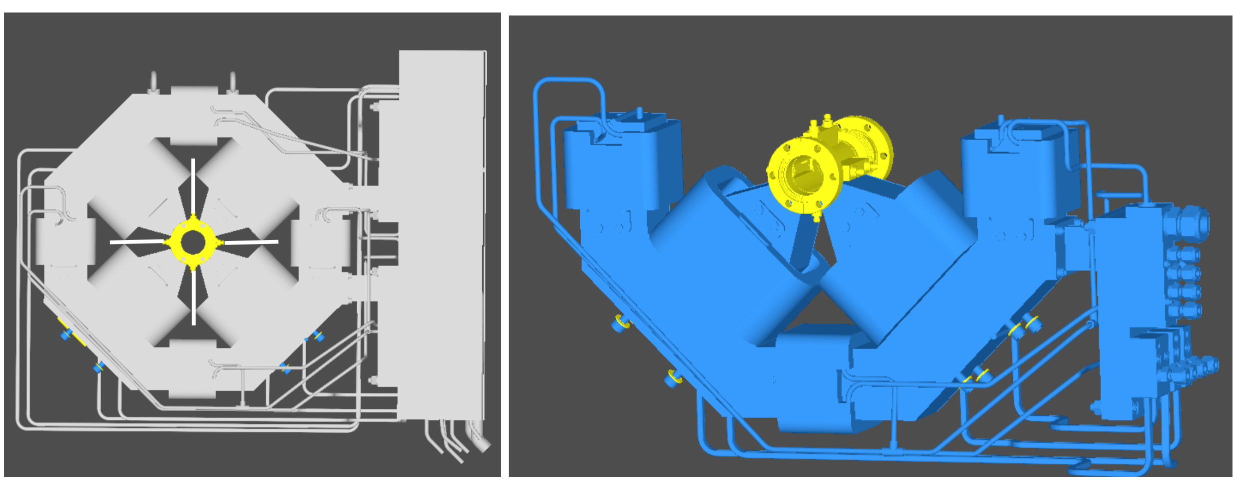

Figure. 3: Full assembly of BPM-Quadrupole (left) and lower part of assembly (right).

However, the BPM Stripline core design is identical, but the flange to flange length, and below/flange interface of Striplines assembly has to adapt to the mechanical integration constraints of each section of the MEBT (See Fig. 4). Table.4 Shows variation in Striplines flange to flange lengths.

Table. 4: BPM Stripline various types and lengths in MEBT

Type	FF Length (mm)	BPM nº
1	143.9	1
2	129.8	5
3	100	4,7
4	143.9	2,3,6
5	133	8

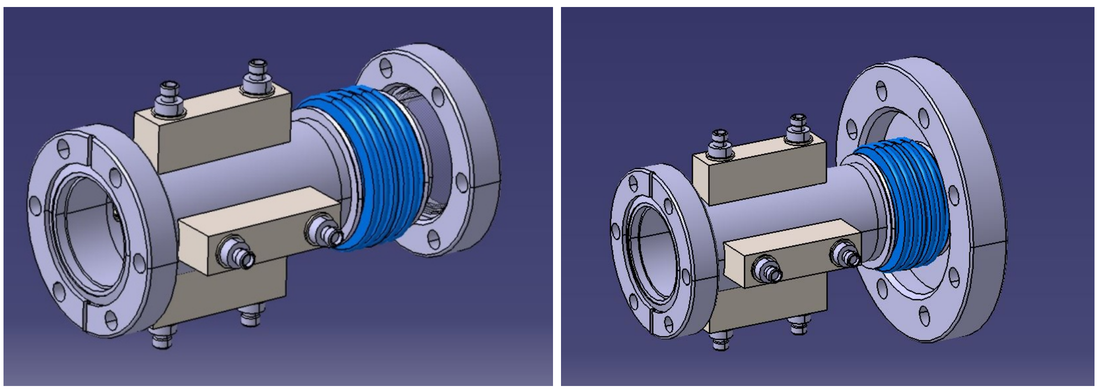

Figure. 4: BPM type 1 (left) and type 5 (right).

4.4. ELECTRONICS SPECIFICATIONS

The output impedance of the Striplines is matched to the cables and front-end electronics of 50Ω. The matching guarantees transmission of the maximum signal power and reduce the reflections. Table. 5 gives the electronic specifications, signal input level range and processing frequency.

Table. 5: BPM Electronics specifications

Parameter	Value	Comments
Max input Power	20 dBm	Input absolute limit
Center Frequency	352 / 704 MHz	Configurable
Bandwidth (3dB)	1 MHz	
Bandwidth (60 dB)	35 MHz	
Crosstalk	<-60 dB	
SNR	˜ 60 dB	
Input Power range	-60 dBm to 5 dBm	
SFDR	60 dBc	
Nonlinearity	<0.1 dB	Over the Dynamic range
Noise Figure	10 dB	

5. ELECTROMAGNETIC MODEL

Since the MEBT energy is far lower than proton relativistic energy β=0.99, a 3D low β electromagnetic model of BPM has been generated and analysed. The parameters of the model are based on the beam parameters of MEBT, other mechanical and electrical constraints and boundary conditions.

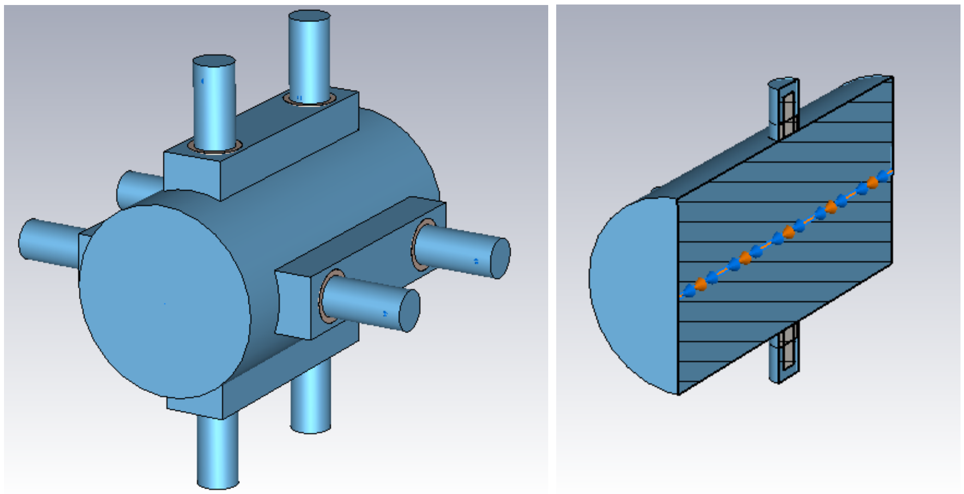

Figure. 4: Screenshot of 3D analysis for Stripline model (left) and Button model (right).

Several electromagnetic simulation iterations have been performed to get the optimum parameters of the design. The frequency of interest was 704.4 MHz, since the processing electronics are based on this frequency. However, the characteristics at first harmonic and higher frequency also has been considered. The other beam parameters like energy, bunch length and current also has been introduced in the model.

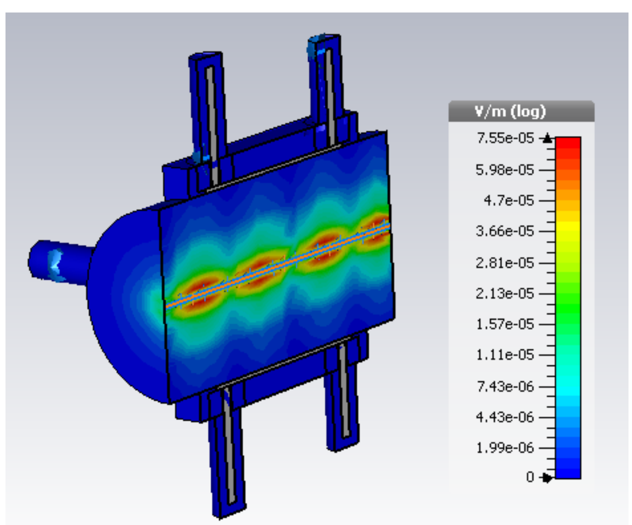

Figure. 5: Screenshot of the Stripline low energy simulation for 704 MHz.

One should notice, that from the first electromagnetic design, to produce the definitive mechanical design, several changes have been introduced due to mechanical restrictions; that also required to go through an electromagnetic optimization process. This iterations were conducted untill a design which conformed both electromagnetic and mechanical restrictions was achieved. Furthermore, for the electromagnetic design, the dimension of the SMA feedthrough was integrated in the model, and the whole model has been analyzed as signal port device, in order to reduce the possible mismatch of feedthrough at higher frequencies. Simulations show high dependence of the characteristics impedance of the BPM to the material, spacer dimensions and gap between the electrode and the body wall. So, the alumina AL_2O_3 as spacer was chosen to secure the gap distance within required tolerances. Other materials like MACOR was found not to provide higher performance than alumina; in addition, has lower thermal conductivity of 1.46 W/m^{0}C in comparison to the alumina 96% with thermal conductivity of 24.7 W/m^{0}C. The gap between electrode and the body is 5±0.01 mm. The characteristic impedance reference is 50 Ω, and the length of the strips in combination with the strip thickness have been optimized in order to produce high signal amplitude at 704.4 MHz.

5.1. STRIPS LENGTH VARIATION

The transfer impedance of the Stripline is a function of the length of strips. Various possible lengths of strips have been analysed and the transfer impedance as a function of frequency component and strip length is found (Fig 5). The graphs show a transfer impedance of 1.6 Ω for a strip length of 42 mm at frequency of 704 MHz (blue curve in the Fig. 5).

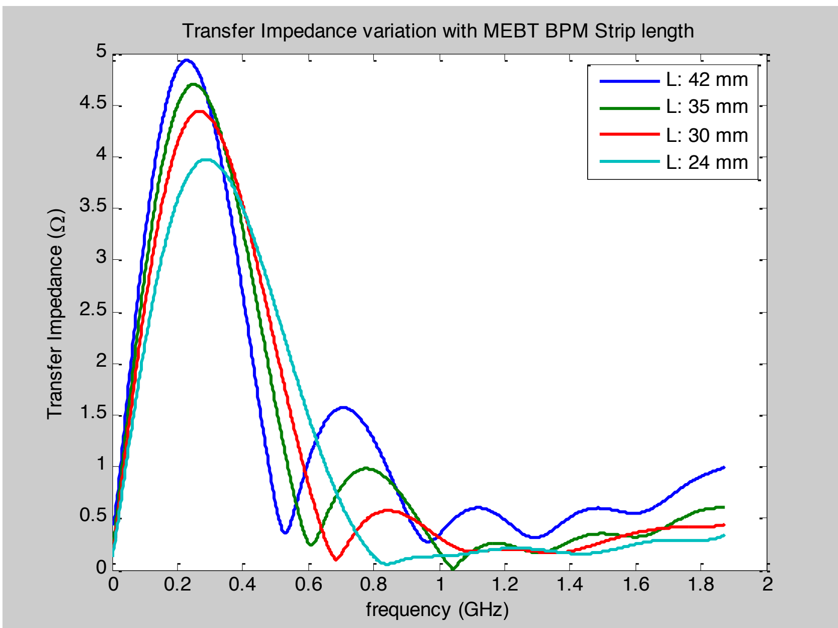

Figure. 5: Transfer impedance changes with variation in Strips length.

5.2. TERMINATION IMPEDANCE VARIATION

Various analysis for different types of termination, including a comparison button type electrodes (ϕ:7.6mm) have been performed. Fig. 6 shows the variation in transfer impedance for different terminations. This figure shows a transfer impedance of 1.6Ω, 1.1Ω and 0.65Ω for matched, shorted terminations and button pickup.

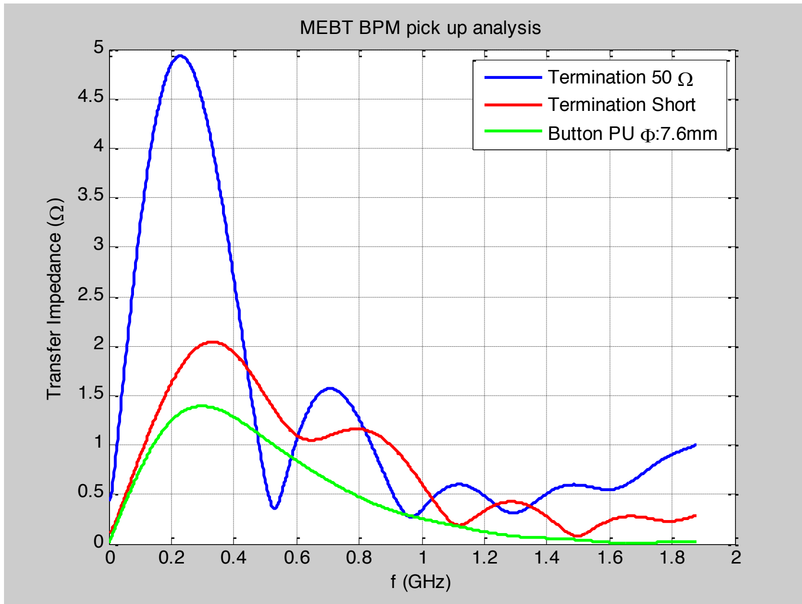

Figure. 6: Comparison of Button pu, short and 50Ω terminated Striplines.

5.3. **SINGLE-BUNCH SIGNAL AMPLITUDE**

Fig. 7 shows that bunch length within MEBT varies from σ: 60ps to σ: 180ps along different locations of BPMs. Variation in bunch length will change the frequency components of the bunch. Therefore, has slight effects on the Stripline voltage shape and amplitude. Analysis for various bunch lengths are shown in Figs. [8-9].

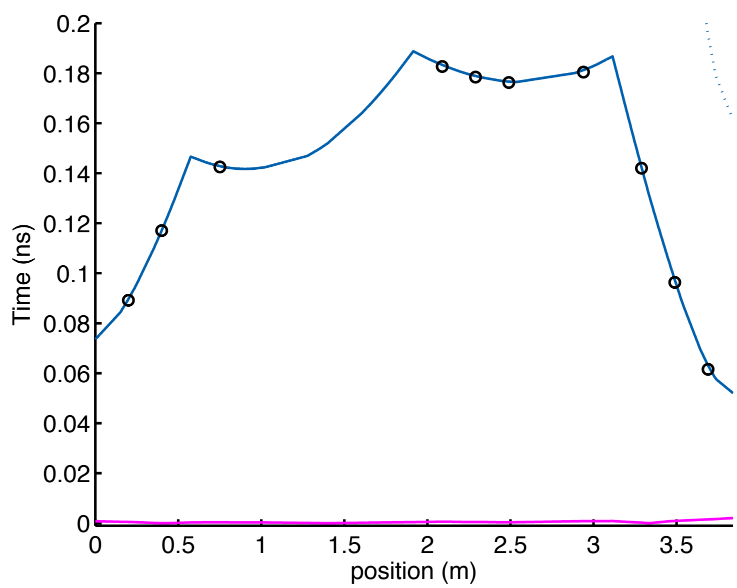

Figure. 7: Longitudinal distribution along the MEBT. Magenta line represents beam centroid, blue lines represent RMS beam size, black circles represent centre of quadrupoles, expected to host BPMs.

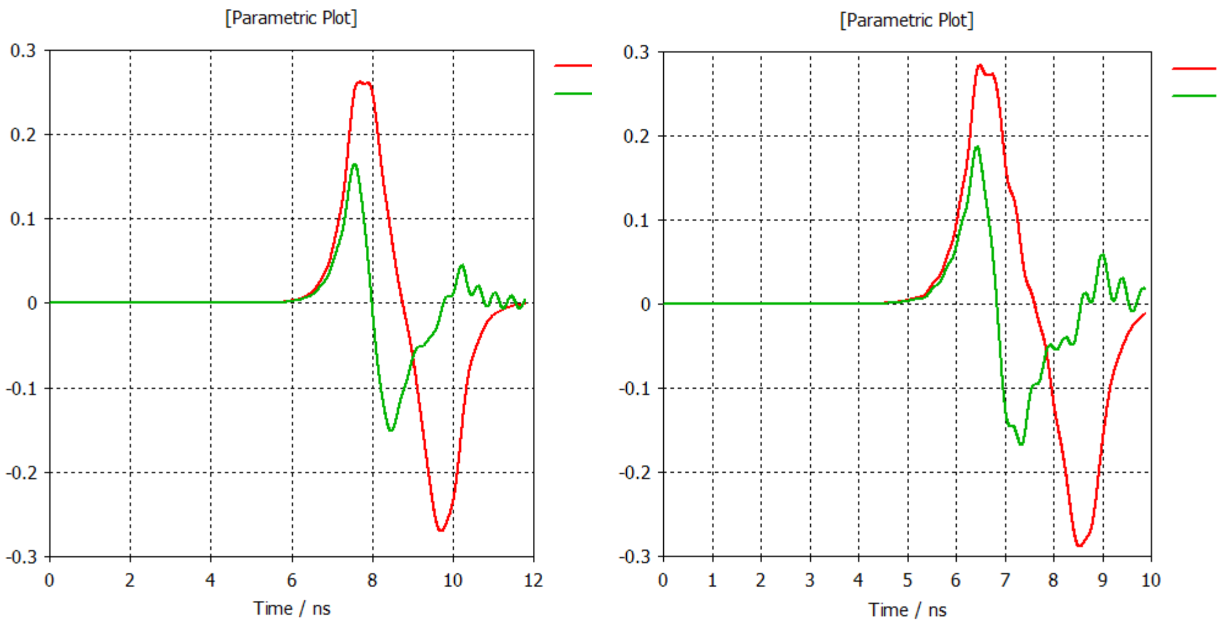

Fig. 8: Stripline electrode voltage for σ: 4.2 mm (left) and σ: 3.5 mm (right).

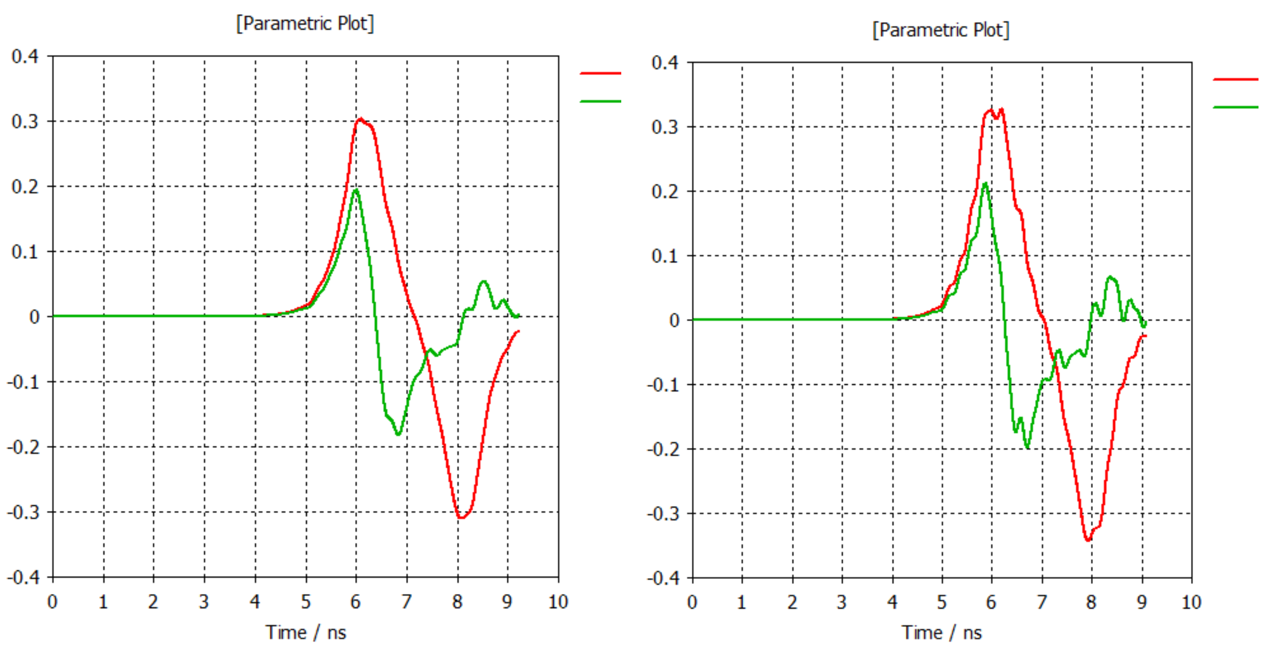

Fig. 9: Stripline electrode voltage for σ: 3.2 mm (left) and σ: 2.8 mm (right).

In the Figs. [8,9], the graphs with colour red and green correspond to Stripline electrode voltage with 50Ω and short termination. In agreement with transfer impedance analysis, the total voltage also shows increasing the voltage amplitude with a matched 50Ω impedance.

5.4. **MULTI-BUNCH SIGNAL AMPLITUDE**

Since thousands of consecutive bunches exist in a single MEBT beam pulse, the head and tail of induced signal of one bunch could overlap with the ones from adjacent bunches. The MATLAB analysis for the multi-bunch was performed and the voltage signal vs. time for a centred beam is shown in fig. 10. The frequency of bunch buckets is the MEBT RF frequency of 352.2 MHz and β=0.088 (Table.3).

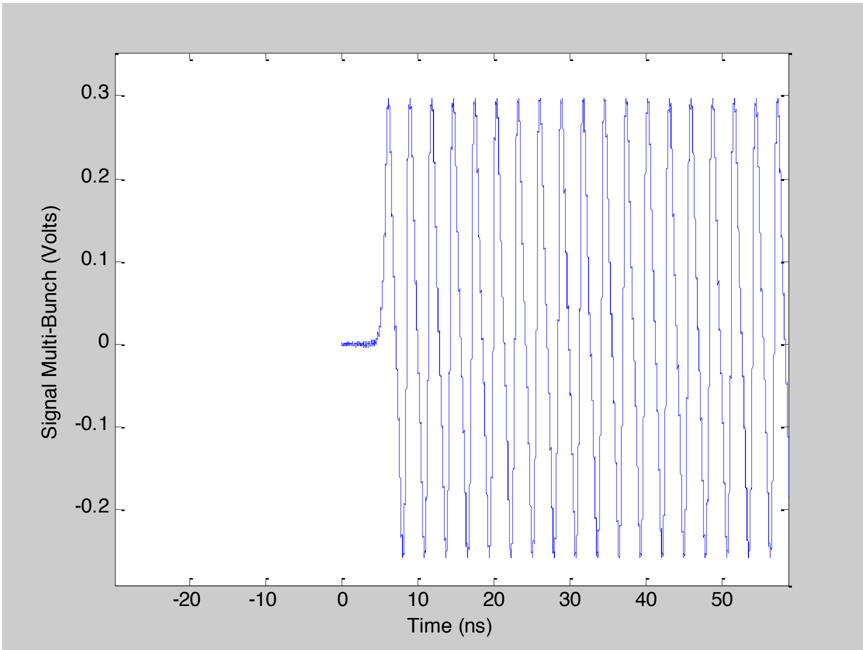

Figure. 10: Multi-bunch expected signal on the Stripline electrodes.

5.5. **SIGNAL RESPONSES AND COUPLINGS**

In order to match the stripline output impedance to the electronics input impedance of 50 Ω, the high frequency analysis of the BPM block was part of the design process. Furthermore, the high frequency coupling between adjacent and opposite electrodes are extracted from the s-parameters.

The s-parameters have been analysed with the detailed mechanical dimensions of components. In the model, the full BPM set including material properties, dimensions of the strips, strip thickness, wall distance, vacuum feedthrough, vacuum tube, and ceramic spacer has been introduced.

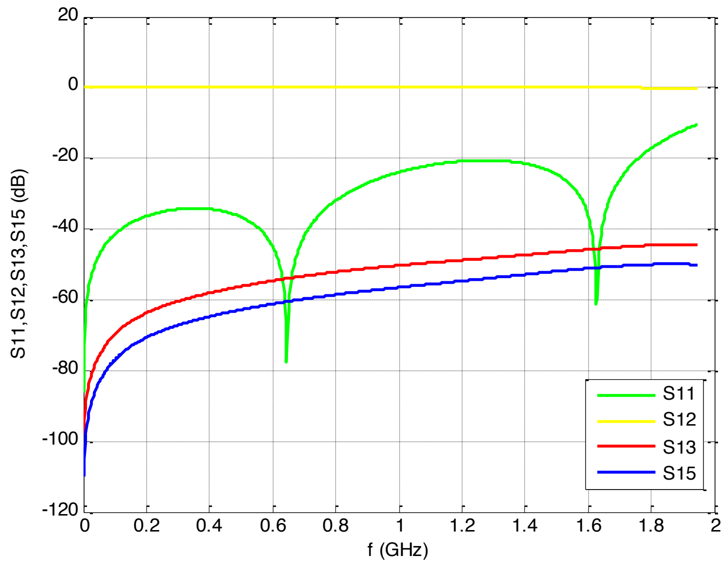

Figure. 11: S-parameters of the stripline.

Fig. 11 shows the s-parameters extracted from the CST 3D model simulations. In the graph, S11 shows the mismatch of one strip, S12 corresponds to signal transmission, S13 corresponds to the signal coupling between adjacent strips and S15 shows the signal coupling between opposite strips.

5.6. **SIGNAL POWER COMPARISON**

In order to estimate the signal power budget out of the pick ups, signal power simulations have been performed for multi-bunch pulses. Figs [12,13] show the signal power for various configurations of the BPM pick-ups at RF harmonics.

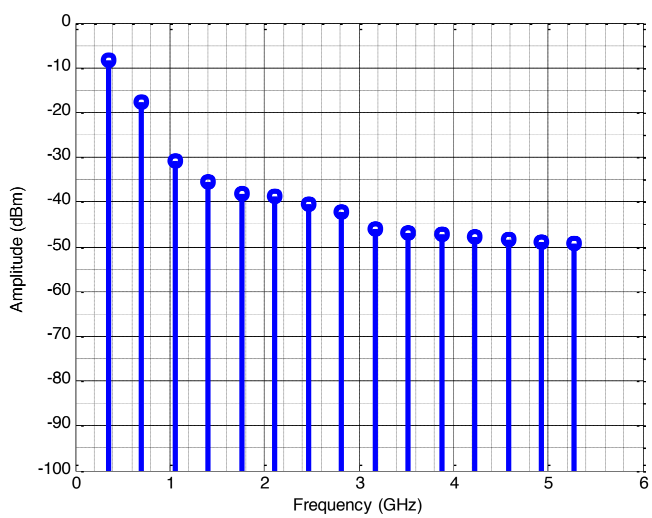

Figure. 12: Signal power level for Stripline with matched termination vs. frequency.

In the Fig. 12, the signal power at the stripline output port for frequency of 704.4 MHz, has a value of -16.5 dBm. A full analysis for various configurations of the BPM pick-ups, considering the MEBT parameters has been performed (Fig. 13). In the figs. [12,13], the cable losses are excluded from the signal values.

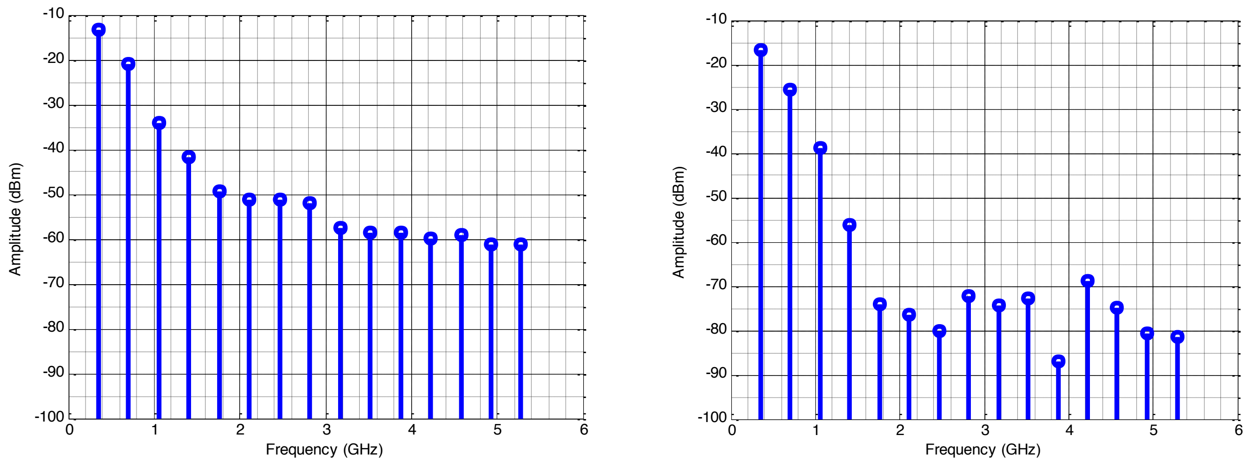

Figure. 13: Signal power level for short termination (left) and a capacitive button with ϕ:7.5mm(right).

In the Fig. 13, the signal power at the pick-up output port for frequency of 704.4 MHz, has a value of -21 dBm for a short termination stripline (Fig. 12, left graph). The value of signal power for frequency of 704.2 MHz, corresponds to -26 dBm for a capacitive button pick-up (Fig. 13, right graph). The analysis shows large difference in signal power level for different configurations. In order to have the highest signal level, the stripline design is based on the matched termination of 50Ω. This guarantees the higher relative S/N ratio and therefore better beam positioning accuracy.

6. BPM STRIPLINE SENSITIVITY

Simulation analysis has been performed to evaluate the sensitivity of responses of electrodes to the beam position displacement. In the analysis, the beam centre has been displaced in horizontal and vertical planes, and the electrode voltage has been evaluated, keeping other beam parameters as the values within MEBT. Since the design has a full quadrant symmetry, therefore the sensitivity in X and Y planes are expected to be identical.

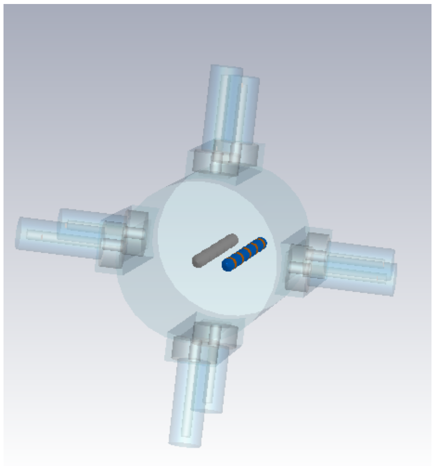

Figure. 14: An screenshot of a displaced beam in the BPM stripline model.

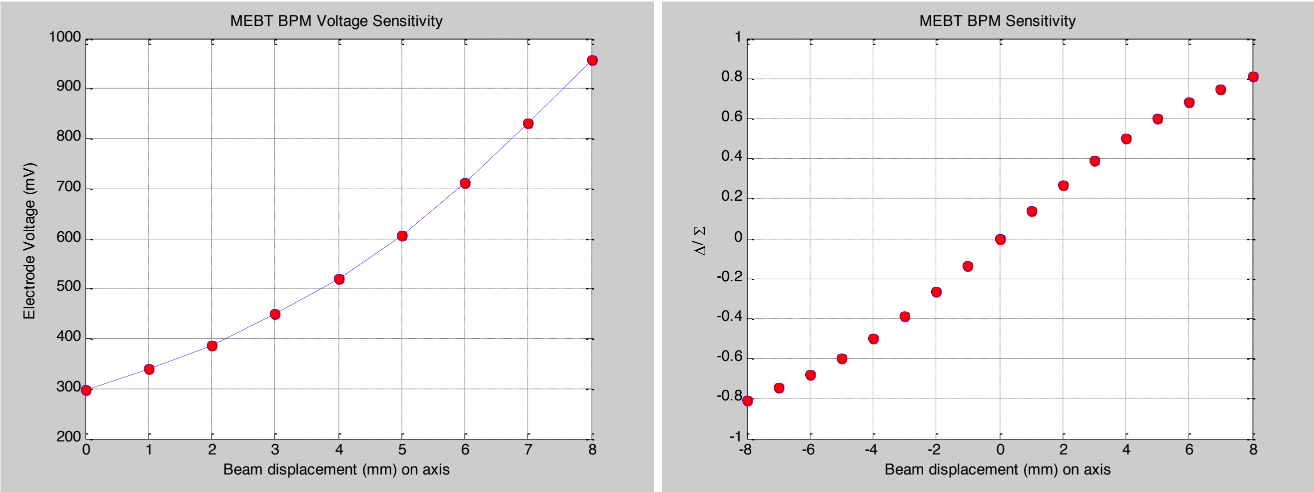

Figure. 15: Sensitivity analysis for BPM Stripline with an off-center beam.

The left frame of Fig. 15 shows the electrode voltage development vs. beam center displacement. It shows a linear variation close to the center, while starting the non-linearity when distancing from the center. At the same time, the values of total voltage amplitude increase from 290mA to 950 mA when the beam displaces 8 mm from the beam pipe center. The right frame of Fig. 15 shows the non-linearity of the Δ/Σ interpretation. Again, in this graph, the non-linearity of the beam positioning is starting when the beam gets off-center at larger distances.

7. CABLE TYPE SELECTION

The connectors of the BPM pick-ups are SMA type in order to fit inside the quadrupole yoke gaps. The N-type connector, however has good mechanical rigidity and RF characteristics, but due to its large mechanical dimensions, could not be selected during the design of BPM sets. The cables to the electronics are low attenuation, with relative large diameters; while the short cable out of the BPM pick-ups could have maximum outer diameter of 5 mm. In order to convert the connector and cable type, a patch panel has been foreseen. The short cables are chosen as ECO142 (Equivalent RG142) with low attenuation, fire resistance (UL1581 VW1 / IEC 332-1) and halogen free (IEC 754-2) characteristics (See Table 6,7). The estimated length of short cable is 85cm.

Table. 6: Cable construction dimensions

Center conductor	**Solid OFC copper**	**0.95 mm**
Dielectric	foam PE	2.85 mm
Inner shield	Al foil	3.10 mm
Outer shield	Tinned copper braid	3.50 mm
Jacket	Black LSZH PE	4.50 mm

Table. 7: Cable electrical characteristics

Characteristic impedance	50Ω ± 2Ω
Operating frequency range	DC - 3 GHz
Shielding effectiveness	80 dB (DC - 3 GHz)
Voltage withstanding	5 000 V rms
Capacitance	87 pF / m
Velocity of propagation	77 % (4.3 ns / m)
Attenuation calculation (dB/m)	(0.385 x √f GHz) + (0.02 x f GHz)

8. **REFERENCES**

[1] CST Studio, www.cst.com

[2] Radiall cables, www.radiall.com