CHARACTERIZATION OF BUTTON AND STRIPLINE BEAM POSITION MONITORS AT FLASH

Summer Student Programme 2007
DESY- Hamburg

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CONTENTS:

Abstract

This report contains the characterization of button and stripline beam position monitors (BPMs) which I did for FLASH (Free electron LASer in Hamburg) during the summer student programme DESY-Hamburg in 2007.
The report describes how I simulated using CST programs. Finally I will explain the results given in simulation of button and stripline BPMs.

1. INTRODUCTION

During the summer students programme 2007 in Hamburg I worked in the MDI (Maschine, Diagnose und Instrumentierung) group. My work includes simulations of button BPMs (Beam Position Monitors) and of stripline BPMs using CST codes, such as Microwave Studio and Particle Studio.
Monitor characteristics, including constant and capacity values were calculated for beam position monitors in this study.

2. AN OVERVIEW OF FLASH

FLASH

FLASH, the Free-Electron Laser in Hamburg, built at DESY, is the first free electron laser world wide to produce femtosecond pulses of soft X-rays, through the principle of Self-Amplified Spontaneous Emission (SASE). FLASH is user facility for an entirely coherent, bright and ultrashort pulses of extreme-ultraviolet radiation and soft X-rays enabling researchers to explore the temporal evolution of physical, chemical, and biochemical processes happening in femtoseconds or picoseconds. Up to now, FLASH has produced ultrashort femtosecond X-ray pulses with wavelengths from 32 nm down to 13 nm, and after an upgrade in 2007 the wavelength will be pushed down to 6.5 nm [1]. The linac is also used as a test facility for the X-ray Free Electron Laser (XFEL) [6] and the International Linear Collider (ILC) study [7]. In the future, these projects open entirely new fields of research [1]. The layout of FLASH linac is shown in figure1.

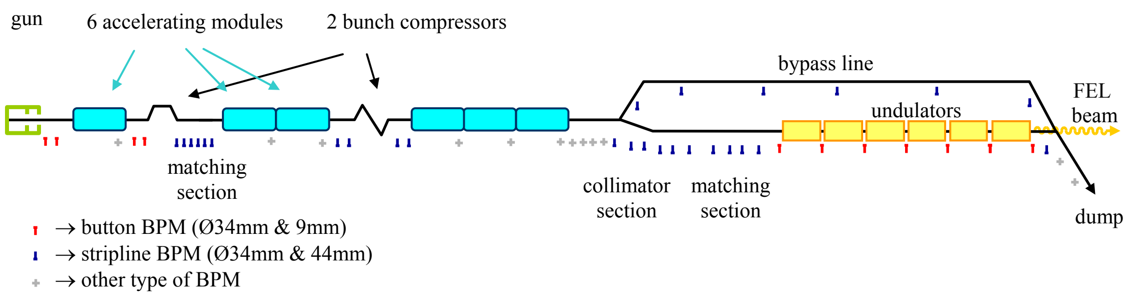

FIGURE 1. Sketch of the FLASH linac [5].

The electron source:

The electron bunches are produced in a laser-driven photoinjector. With the help of a laser sent on the photo-cathode, the gun generates beams with up to 800 electron bunches spaced by 1 μs. The photoinjector is mounted inside a Radio-Frequency (RF) cavity. The bunch charge is between 0.5 and 1 nC.

The superconducting linear accelerator:

The electrons are accelerated to energies between 450 and 700 MeV in several superconducting cryo-modules, and after the upgrade the energy will be raised to 1 GeV. Eight 1m-long superconducting cavities, which are made from pure niobium and consist of nine cells, are built in each cryo-module [1].

Bunch compression:

The electron bunches are longitudinally compressed, in 2 magnetic chicanes increasing the peak current from initially 50 A to several 1000 A as required for the FEL operation.

The undulator magnet:

At the end of the linac the electron bunches pass through a magnetic configuration called undulator which is made from iron pole shoes with NdFeB permanent magnets in between. The undulator must be more than 20 m long for wavelengths in the 10-nanometer regime. The FLASH undulator system has six magnets of 4.5 m length each [1]. Several collimators are used mainly to protect the 6 undulators.
A dipole magnet deflects the electron beam into a dump, while the FEL beam goes further to one of several user beam lines. The bypass line has the role of the protecting the undulators during machine studies.

Experimental Stations

The photon beam transport system delivers the FEL pulses to one out of five experimental stations by remotely controlled plane grazing incidence mirrors [1].

BPMs at FLASH

Beam position monitors are an important part of the diagnostics at FLASH, since the electron beam trajectory is essential for the FEL beam quality. The BPM system consists of more than 60 BPMs, most of them also shown in figure1. Various kinds of BPMs are installed [2]: stripline BPMs in most linac, with a beam-pipe diameter of 34 or 44 mm, button BPMs in the injector (diameter 34 mm) and undulators (diameter 9 mm), and cavity and re-entrant cavity BPMs in the cryo-modules. The stripline and button BPMs at FLASH make the object of this study and will be described in detail in the next chapter.

3. AN OVERVIEW OF BEAM POSITION MONITORS (BPMs) AT FLASH

The Principle of BPMs

BPMs are essential instruments in any particle accelerator, monitoring the beam trajectory [3]. They consist typically of 4 symmetrically arranged pick-up electrodes, for example left, right, up and down as shown in figure 2. Particle bunches induce a voltage V on each electrode. By comparing signals from the two opposite pick-ups, the transverse beam position is calculated.

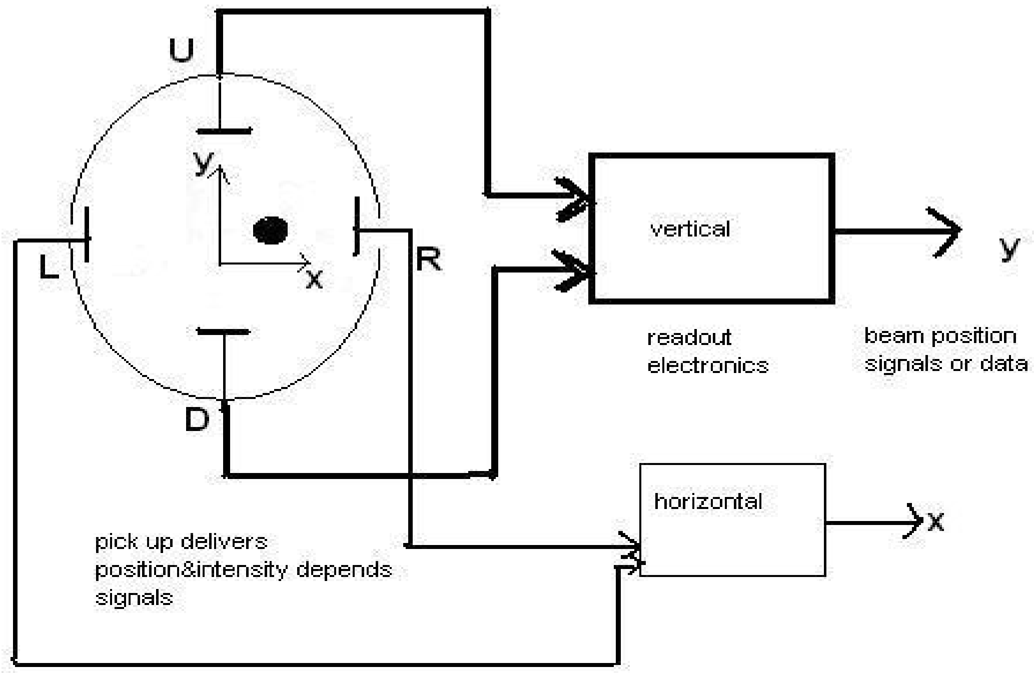

FIGURE 2. BPM system [3]

Depending on the readout electronics, the beam position is calculated in one of the following ways:

$(V_R - V_L) / (V_R + V_L)$ or $\arctan (V_R / V_L)$

The electronics of most FLASH BPMs is based on the second formula [2].

Types of Beam Position Monitors at FLASH

There are several types of BPMs at FLASH [2,5]. Most of the BPMs are button and stripline BPMs, while in the cryo-modules cavity and re-entrant cavity BPMs are installed. The button and stripline BPMs are the object of this two months project.

BUTTON BPM

Buttons are a variant of the capacitive monitor, terminated into a characteristic impedance (usually by a coaxial cable with impedance 50 Ω).

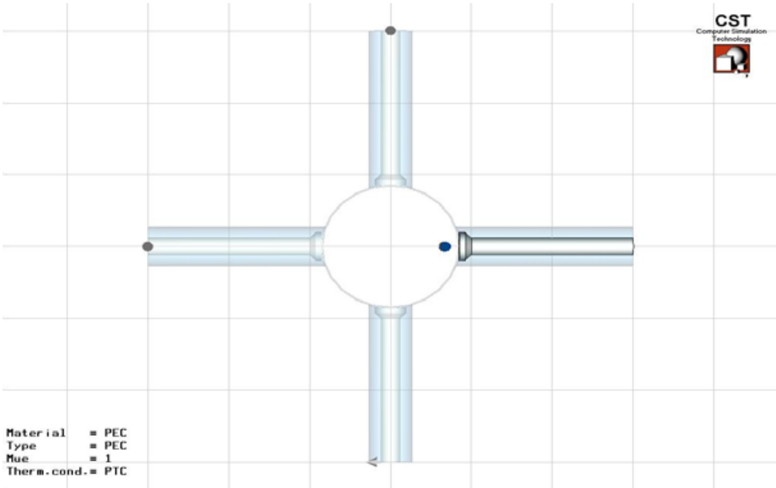

FIGURE 3. Section through the 34 mm button BPM

Button BPMs are used in the injector area and between the undulators of FLASH.
Figure 3 shows schematically a section through a BPM installed in the injector area of FLASH. Four pick-up antennas are placed symmetrically around the beam pipe with a diameter of 34 mm and each is terminated with a "button" which is tangential to the beam pipe.

FIGURE 4. Pick-up electrode for the 34 mm FLASH button BPM

Figure 4 shows a picture of a "button" pick-up electrode.

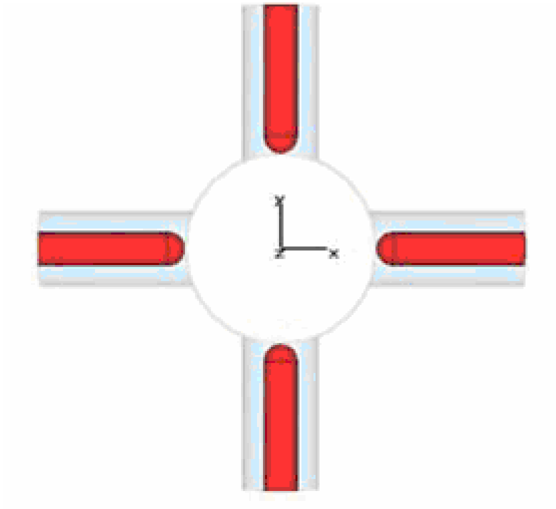

FIGURE 5. Button BPM (for undulator)

Figure 5 shows the button BPM installed in the undulator vacuum chamber, between the undulators. In this study I have made simulations for both the 34 mm and the 9 mm button BPMs. Chapter 4 presents the calculations of various BPM characteristics.

STRIPLINE BPM

A stripline BPM has four electrodes placed symmetrically around the vacuum chamber and parallel to the chamber axis.

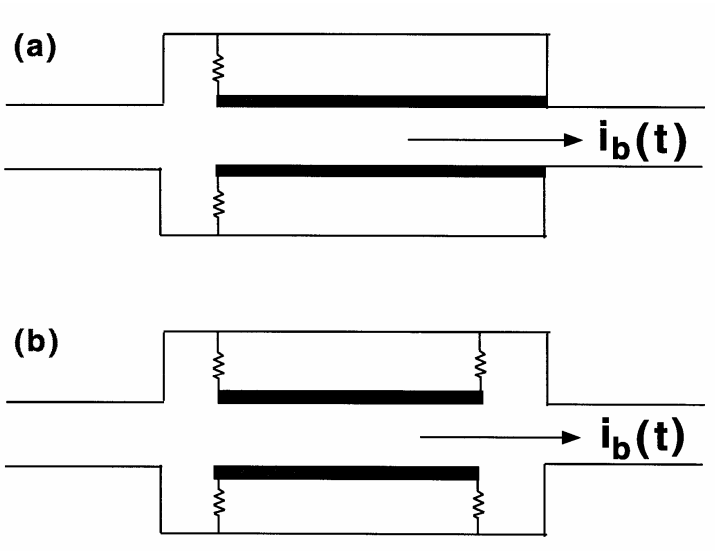

FIGURE 6. Transmission line detector terminated on the right hand side to ground (a) and terminated into matched impedance (b) [3]

Figure 6 shows the stripline BPM principle. In Fig.6a shows unterminated transmission line and Fig. 6b shows terminated line.

FLASH has transmission line detector terminated into matched impedance. (see Fig.6b)
The readout electronics is connected at the upstream end of the "striplines" while the downstream and is terminated in a 50 Ω load.

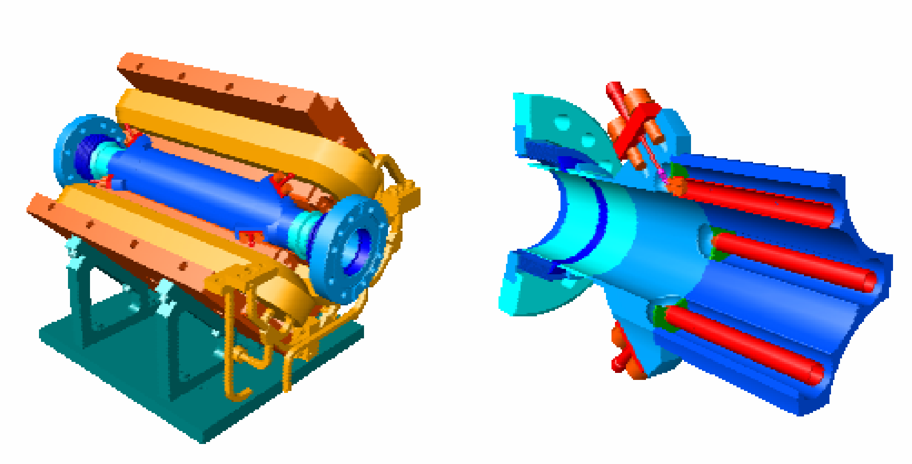

FIGURE7. FLASH stripline BPM inside quadrupole installation and sectional view [2]

Figure 7 shows FLASH stripline BPM and section of BPM in the quadrupole magnet. The gold-plated stainless-steel tube electrodes provide high mechanical stiffness.

In this study, we have considered the two stripline BPM types in FLASH: one of them has 34 mm diameter and the other 44 mm diameter. Chapter 5 shows the simulations for both types.

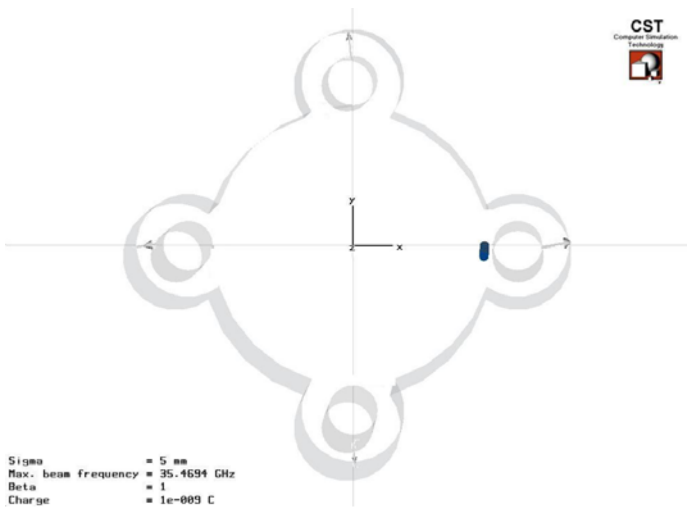

FIGURE 8. Section of stripline BPM with voltage monitors

Figure 8 shows the section of stripline BPM.

4. SIMULATION OF BUTTON BPMs

Microwave Studio and Particle Studio are very useful programmes to calculate and simulate. For instance CST Microwave Studio (MWS) is a tool for the fast and accurate simulation of high frequency devices. MWS quickly gives electromagnetic behaviour of high frequency designs. Beside the time domain simulator which uses proprietary perfect boundary approximation technology, MWS offers frequency domain on hexahedral and tetrahedral meshes, an integral equation solver for big structures [4].

4.1. 34 mm Button BPM

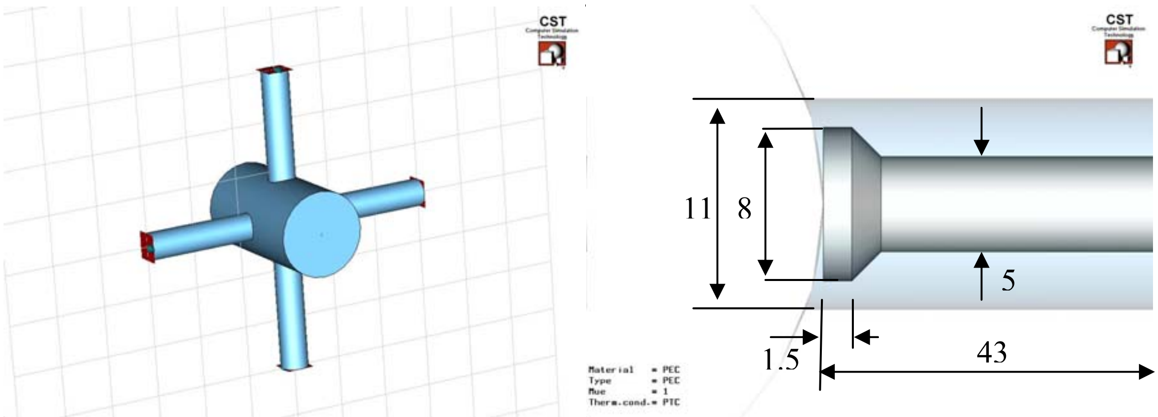

FIGURE 9.a) Button BPM (34 mm diameter of beam pipe) **b)**with dimensions

First we modeled the 34 mm button BPM. The dimensions of the monitor (in mm) are given in figure 9b. The vacuum chamber and the channels for the pick-ups are defined as vacuum and the pick-up electrodes as PEC (perfect electric conducting material). The background is also PEC.

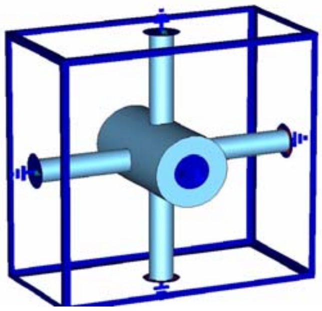

FIGURE 10. Boundary conditions for button BPM

All boundary conditions were chosen as magnetic field (see fig.10), since we want the electric field to be perpendicular on the PEC background, and therefore forbid electric fields perpendicular to the boundary planes.
At the end of the antennas waveguide ports were defined. The ports absorb all energy, equivalent to a perfectly matched load, or the long coaxial cable connected in practice to the pick-ups. At each antenna and voltage monitors are defined.

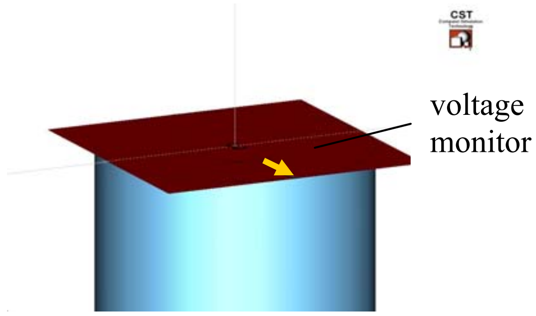

FIGURE 11. A view of port and voltage monitor

One voltage monitor and a port are shown in figure 11.

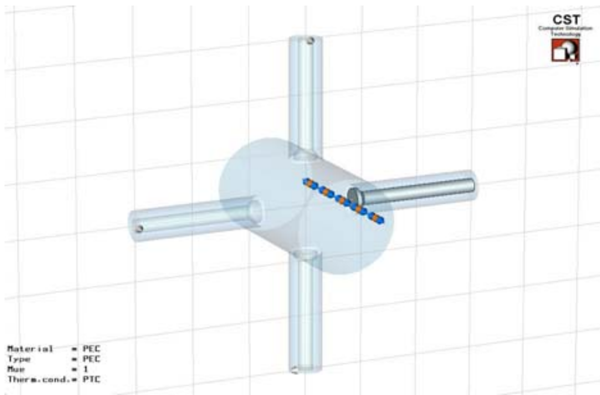

FIGURE 12. A view of beam inside of beam pipe

A bunched beam has been defined (see figure 12 and 13), with the following beam properties:
σ=5 mm
Q=1e-9
σ value is longer than the bunch length in FLASH (1.5 mm and less), but this reduces the simulation time significantly and enables the correct calculation of most BPM characteristics.

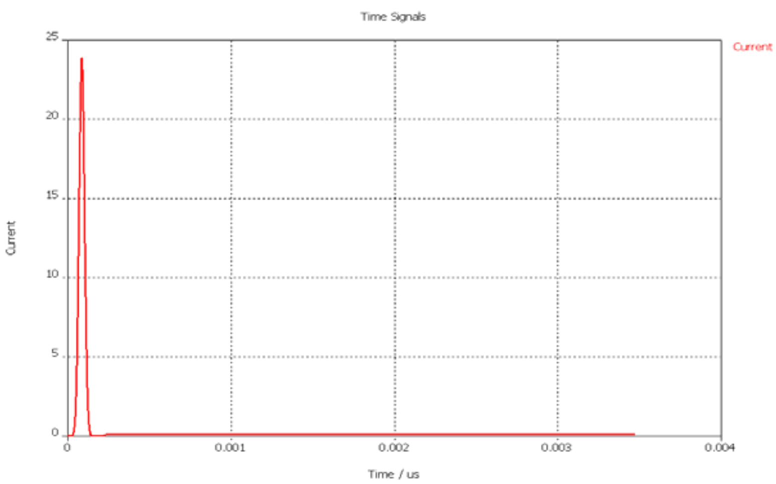

FIGURE 13. Beam current

Figure 13 shows the beam current.

For simulations we use the wakefield solver. As a result we get the voltages at the 4 pick-ups for various beam offsets x and y (see Tables 1-3).

A_R is the amplitude of the voltage at the right antenna V_R, and A_L for the left voltage. For each beam offset, the ratio V_L/V_R has been calculated, as well as:

$$V_{out}(max) = 2*\text{arccot}(A_R(max)/A_L(max)) = 2*\arctan(1/(A_R(max)/A_L(max)) = 2*\arctan(A_L(max)/A_R(max)) ,$$

which simulates the output of the BPM electronics.

Beam offset		V_R	V_L	V_L/V_R **(max)**	V_L/V_R **(max) [dB]**	V_{out} **(max)**
x	**y=0**	A_R**(max)**	A_L**(max)**		**20*log(**V_L/V_R**)**	**2*ATAN(**A_L**(max)/**A_R**(max))**
-16,2	0	44,65	476	10,66069429	20,55570979	2,954534965
-12,2	0	22,14	203,9	9,209575429	19,28479218	2,925274863
-10,6	0	17,49	154,2	8,816466552	18,90589128	2,915709767
-8	0	13,52	104,7	7,74408284	17,7793998	2,884752246
-5,8	0	18,49	77,84	4,209843158	12,48531832	2,675160087
-3,5	0	24,91	58,29	2,340024087	7,384406556	2,333880503
-2,1	0	29,62	49,16	1,659689399	4,400536401	2,057048404
0	0	38,04	38,54	1,013144059	0,113424041	1,583854381
2,1	0	49,16	29,62	0,602522376	-4,400536401	1,084544249
3,5	0	58,29	24,91	0,427346028	-7,384406556	0,807712151
5,8	0	77,84	18,49	0,237538541	-12,48531832	0,466432566
8	0	104,7	13,52	0,12913085	-17,7793998	0,256840408
10,6	0	154,2	17,49	0,113424125	-18,90589128	0,225882886
12,2	0	203,9	22,14	0,108582639	-19,28479218	0,216317791
16,2	0	476	44,65	0,093802521	-20,55570979	0,187057689

TABLE 1. Amplitude of voltages at the right and left antennas, their ratio and V_{out} for various x beam offsets and y=0

Beam offset		V_1	V_2	V_2/V_1 (max)	V_2/V_1 (max) [dB]	V_{out} (max)
x	**y=3**	**A_1(max)**	**A_2(max)**		**20*log(V_2/V_1)**	**2*ATAN(A_2(max)/A_1(max))**
-16,2	3	13,61	349,3	25,66495224	28,18680921	3,06370477
-12,2	3	9,271	163,8	17,66799698	24,94374633	3,028514276
-8,7	3	11,45	101,2	8,838427948	18,92750052	2,916266289
-6,3	3	16,37	75,13	4,589492975	13,23529419	2,712520926
-3,6	3	23,3	54,6	2,343347639	7,396734434	2,334905739
-2,2	3	27,66	46,39	1,677151121	4,491443935	2,066278676
0	3	35,77	36,24	1,013139502	0,113384977	1,583849884
2,2	3	46,39	27,66	0,596249192	-4,491443935	1,075313977
3,6	3	54,6	23,3	0,426739927	-7,396734434	0,806686915
6,3	3	75,13	16,37	0,217888992	-13,23529419	0,429071727
8,7	3	101,2	11,45	0,113142292	-18,92750052	0,225326364
12,2	3	163,8	9,271	0,056599512	-24,94374633	0,113078377
16,2	3	349,3	13,61	0,038963642	-28,18680921	0,077887884

TABLE 2. Similar to table 1 for y=3mm

Beam offset		V_1	V_2	V_2/V_1 (max)	V_2/V_1 (max) [dB]	V_{out} (max)
X	**y=6**	**A_1(max)**	**A_2(max)**		**20*log(V_2/V_1)**	**2*ATAN(A_2(max)/A_1(max))**
-12,2	6	9,565	79,84	8,347098798	18,43071108	2,903124984
-10,6	6	9,021	76,6	8,491298082	18,57948174	2,907137329
-8	6	10,85	64,3	5,926267281	15,45562469	2,807261521
-5,8	6	14,99	53,13	3,544362909	10,99076366	2,591612038
-3,5	6	20,15	42,68	2,118114144	6,518987206	2,259403993
-2,1	6	23,79	37,09	1,559058428	3,857247826	2,000963045
0	6	29,75	30,12	1,012436975	0,107359949	1,583156283
2,1	6	37,09	23,79	0,64141278	-3,857247826	1,140629608
3,5	6	42,68	20,15	0,472118088	-6,518987206	0,88218866
5,8	6	53,13	14,99	0,282138152	-10,99076366	0,549980616
8	6	64,3	10,85	0,16874028	-15,45562469	0,334331132
10,6	6	76,6	9,021	0,117767624	-18,57948174	0,234455324
12,2	6	79,84	9,565	0,119802104	-18,43071108	0,23846767

TABLE 3. Similar to table 1 for y=6mm

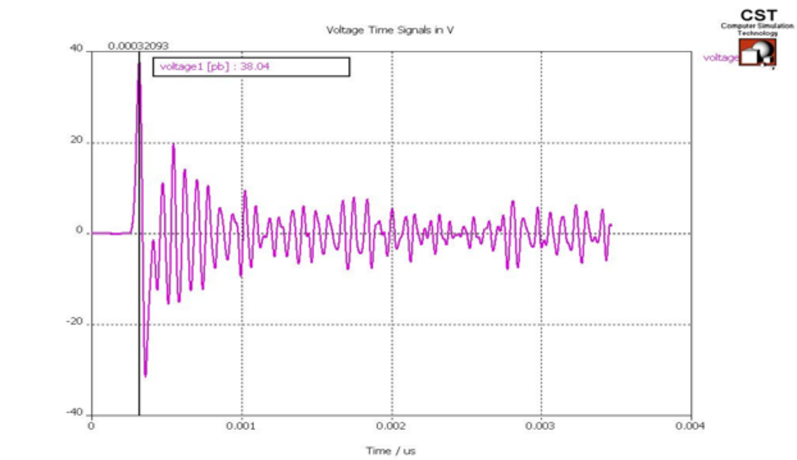

FIGURE 14. Voltage (x,y = 0)

The voltage obtained at one antenna for x=0 and y=0 is shown in figure 14 and has a maximum value of 38.04 V.

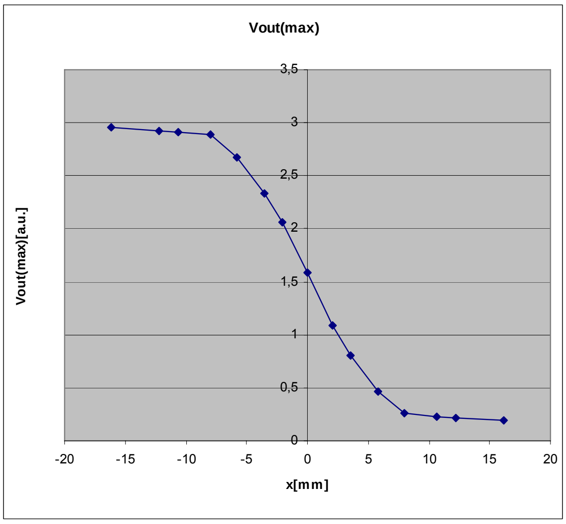

FIGURE 15. V_{out}(max) for table 1

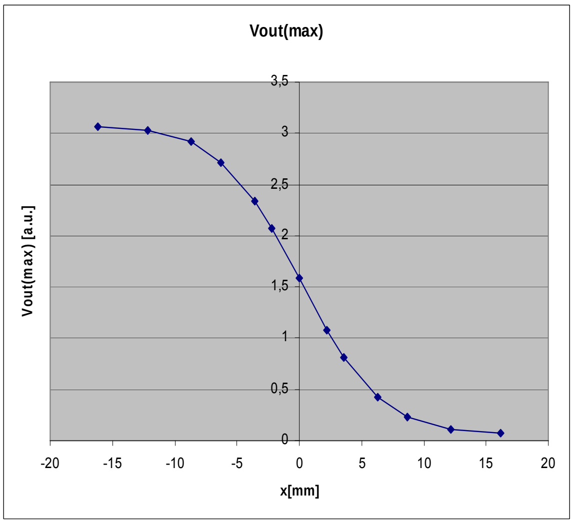

FIGURE 16. V_{out}(max) for table 2

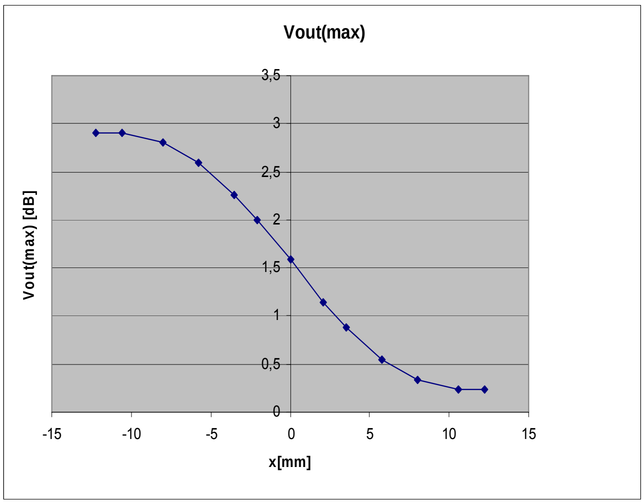

FIGURE 17. V_{out}(max) for table 3

V_{out} for y=0, 3 and 6 mm, corresponding tp table 1-3, is plotted in figures 15-17. Figure 18 shows similar curves for V_L/V_R.

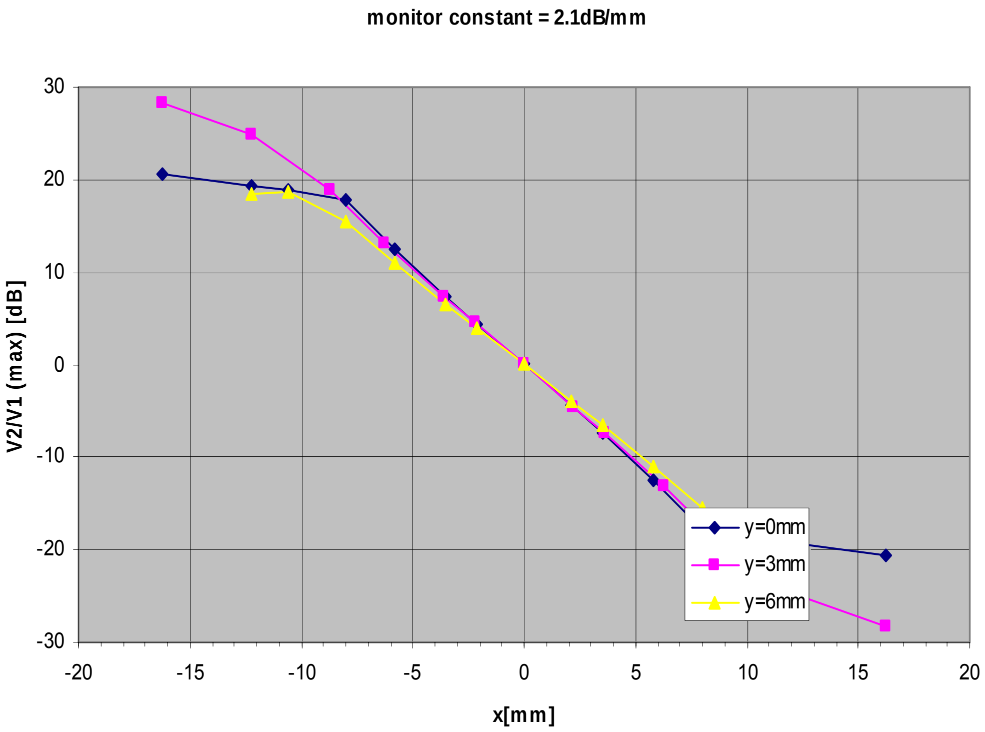

FIGURE 18. V_L/V_R as a function of x for various y-offsets for the 34 mm button BPM

From the slope of V_L/V_R, $\Delta(V_L/V_R)/\Delta x$ for y=0, at x=0, we get the monitor constant K

K = 2.1 [dB/mm] (Φ34 mm button BPM)

Button Capacity

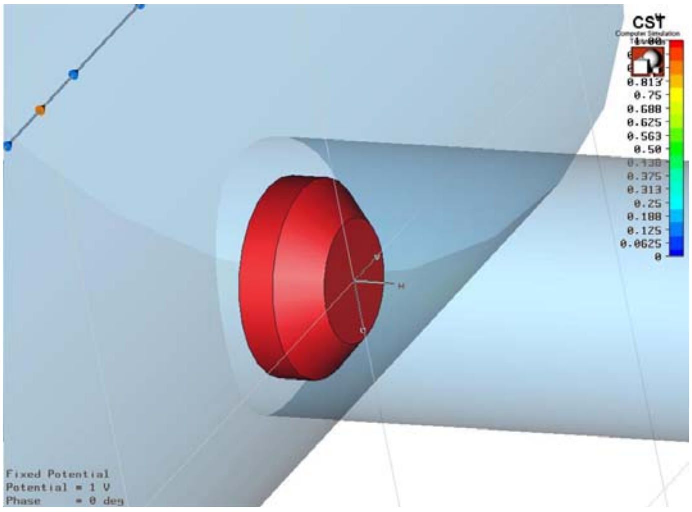

FIGURE 19. Potential of 1V applied to the "button" of one antenna

The electrostatic solver is used to calculate the capacity. Firstly, one antenna was chosen using with electrostatic solver and a potential of 1 V was applied to its button and then started to the simulation (see figure 19).

Button capacity can be calculated in two ways;

- From electric field energy W = 4.43e-013 J

  V=1 V
  $W=CV^2/2$ $C=2W/V^2$ = (2*4, 43e -013)/1
  C= 0,886 pF

- From the charge induced on antenna Q = 8.85e-013C,

  V=1 V
  C=Q/V
  C= 0,85 pF

4.2. 9 mm Button BPM

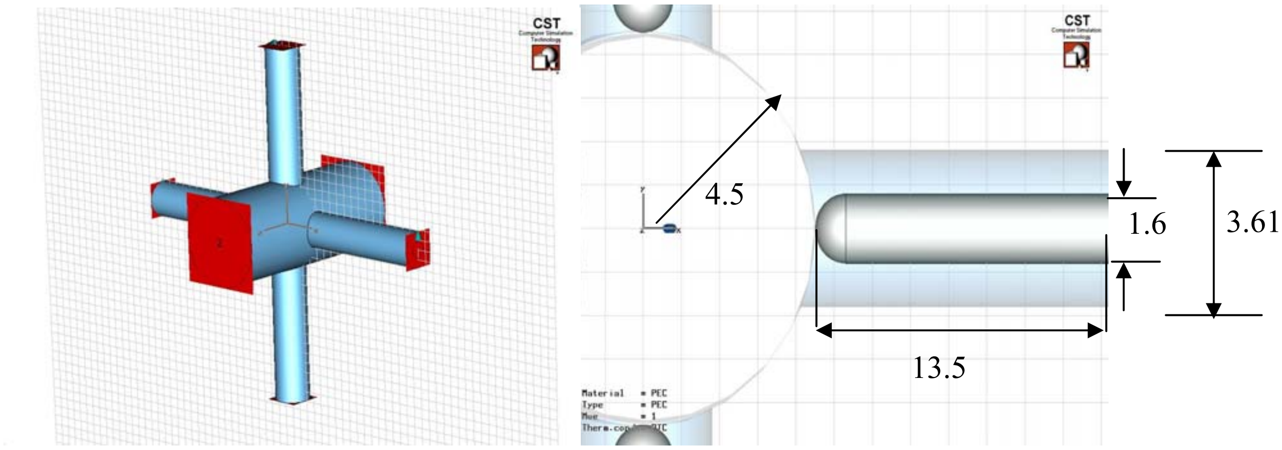

FIGURE 20. a) Button BPM (9mm diameter) **b)** with dimensions

Figure 20 shows the 9 mm button BPM and its dimensions.
The materials, background, boundary conditions, ports, voltage monitors and beam properties were defined as for the 34 mm button BPM (previous subchapter). In addition, ports were also used at the ends of the beam pipes, in order to avoid reflections.

Again we calculated the voltage at the pick-ups for various beam offsets. Tables 4, 5 and 6 show the results for several y-offsets.

Beam offset		**V_R**	**V_L**	**(V_L/V_R)(max)**	**(V_L/V_R)(max)[dB]**	**Vout (max)**
x	**y=0**	**A_R(max)**	**A_L(max)**		**20*log(V_L/V_R)**	**2*ATAN(A_L(max)/A_R(max))**
-4	0	0,996	136,8	137,3493976	42,75653518	3,127031507
-3	0	3,03	65,74	21,69636964	26,72774142	3,049476525
-2,2	0	5,08	40,92	8,05511811	18,12143826	2,894567179
-1,5	0	7,364	28,8	3,910917979	11,84557416	2,640930818
-0,7	0	13,71	19,84	1,447118891	3,210084261	1,932234201
0	0	14,59	14,59	1	0	1,570796327
0,7	0	19,84	13,71	0,691028226	-3,210084261	1,209358453
1,5	0	28,8	7,364	0,255694444	-11,84557416	0,500661836
2,2	0	40,92	5,08	0,124144673	-18,12143826	0,247025475
3	0	65,74	3,03	0,04609066	-26,72774142	0,092116128
4	0	136,8	0,996	0,007280702	-42,75653518	0,014561146

TABLE 4. Similar to table 1 for y=0

Beam offset x	y=2	V_R $A_R(max)$	V_L $A_L(max)$	$(V_L/V_R)(max)$	$(V_L/V_R)(max)[dB]$ $20*log(V_L/V_R)$	Vout (max) $2*ATAN(A_L(max)/A_R(max))$
-3	2	1,768	17,25	9,75678733	19,78613677	2,937320431
-2,2	2	3,4	17,37	5,108823529	14,16641803	2,755000934
-1,5	2	5,062	15,09	2,981035164	9,487341979	2,494276879
0	2	9,539	9,539	1	0	1,570796327
1,5	2	15,09	5,062	0,335453943	-9,487341979	0,647315775
2,2	2	17,37	3,4	0,195739781	-14,16641803	0,38659172
3	2	17,25	1,768	0,102492754	-19,78613677	0,204272223

TABLE 5. Similar to table 1 for y=2mm

Beam offset		V_R	V_L	$(V_L/V_R)(max)$	$(V_L/V_R)(max)[dB]$	Vout (max)
x	y=4	$A_R(max)$	$A_L(max)$		$20*log(V_L/V_R)$	$2*ATAN(A_L(max)/A_R(max))$
-1,5	4	0,6782	1,379	2,033323503	6,164129615	2,227451311
-1	4	1,23	1,946	1,582113821	3,98475449	2,014264263
0	4	1,925	1,925	1	0	1,570796327
1	4	1,946	1,23	0,632065776	-3,98475449	1,12732839
1,5	4	1,379	0,6782	0,491805656	-6,164129615	0,914141342

TABLE 6. Similar to table 1 for y=4mm

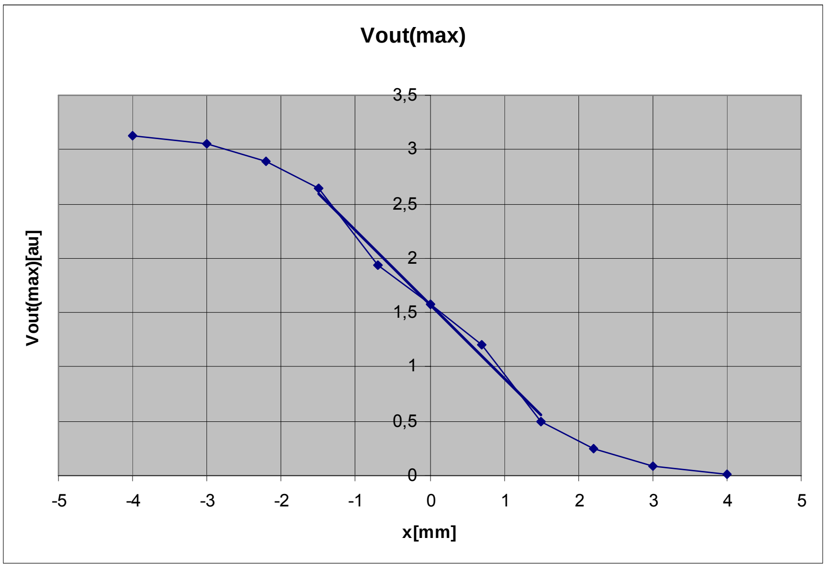

FIGURE 21. V_{out}(max) for table 4

Figure 21 shows V_{out}(max) for values of table 4.

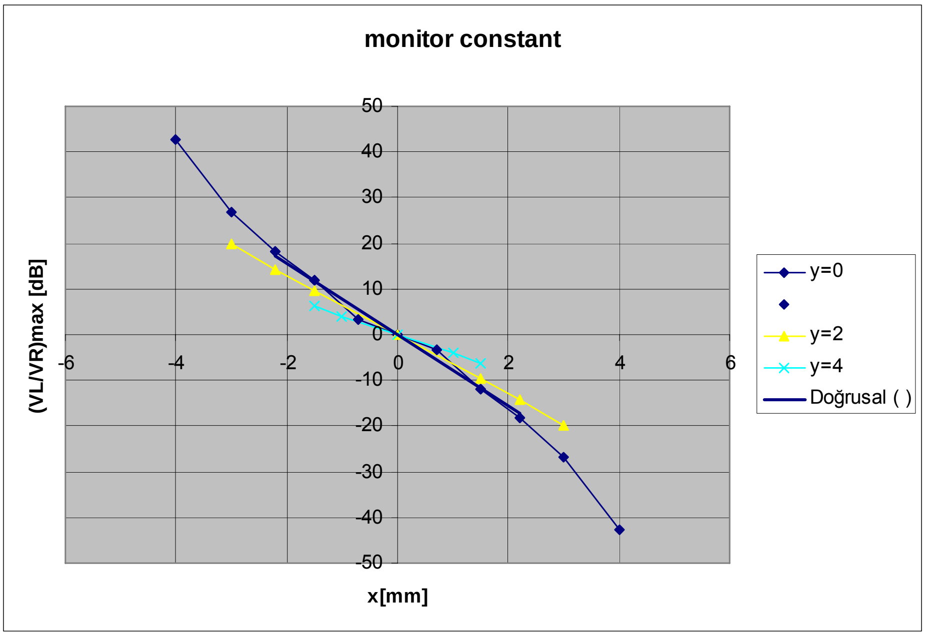

FIGURE 22. V_L/V_R as a function of x for various y-offsets for the 9 mm button BPM

Figure 22 shows V_L/V_R as a function of x for various y-offsets.

The monitor constant K= 8.23 dB/mm for this monitor.

Capacity Calculation For 9 mm Button BPM :

Similarly to the previous subchapter we calculate the button capacity in two ways:

- From energy

  V=1 V, Electric Field Energy W = 4,65e-013 J
  $W=CV^2/2$ $C=2W/V^2$ = (2*4,65-013)/1
  C= 0,93 pF

- From charge

  V=1 V, Q = 9,3e-013 C
  C=Q/V = 9,3e-013/1
  C=0,93 pF

5. SIMULATION OF STRIPLINE BPM

5.1. 34 mm Stripline BPM

FIGURE 23. a) Stripline BPM (34 mm diameter) **b)** with dimensions (the beam pipe length is 200 mm)

Figure 23 shows the stripline BPM for a beam pipe with 34 mm diameter, and its dimensions. The beam pipe and the stripline channels are defined as vacuum and the striplines as PEC. The boundary conditions are magnetic. Two ports have been defined at the end of the model.

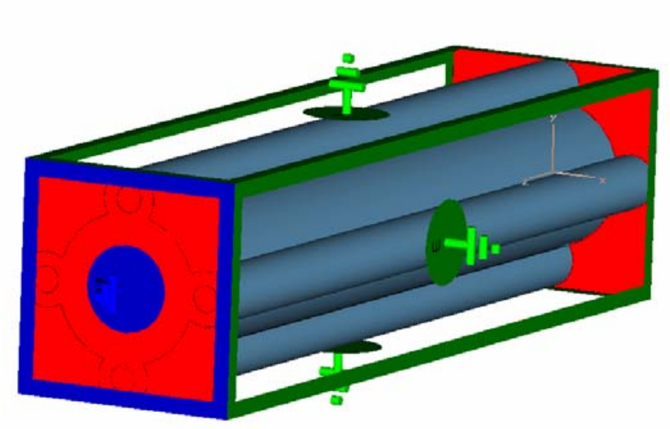

FIGURE 24. Boundary conditions for stripline BPM (34 mm diameter)

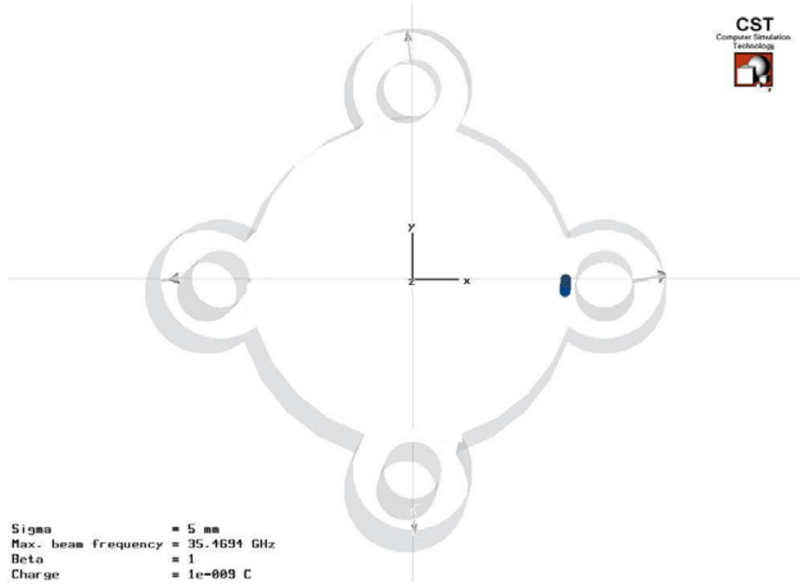

FIGURE 25. Voltage monitors for stripline BPM (x=16, y=0)

Similarly to the button BPM, a beam and voltage monitors between each stripline and the channels have been defined (figure 25).

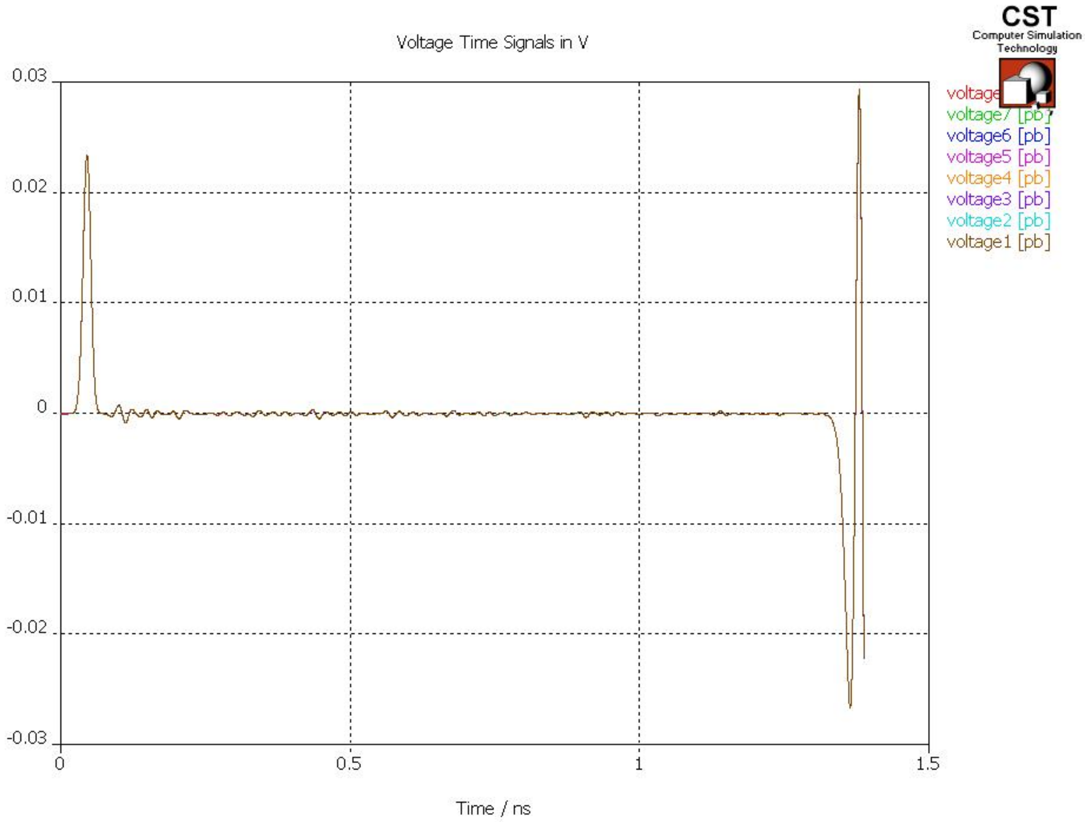

FIGURE 26. Voltage value of V_R (x=0, y=0, σ =2 mm)

The voltage resulted for a centered beam with σ=2mm is shown in figure 26. The distance between the positive and negative pulses is given by the monitor length.

Table 7 gives the voltages resulted for various x beam offsets, for y=0. The same formula was used to calculate $V_{out}(max)$ (see page 11). Vout and V_L/V_R are plotted in figures 27 and 28.

Beam offset x	y=0	V_R $A_R(max)$	V_L $A_L(max)$	$(V_L/V_R)(max)$	$(V_L/V_R)(max)[dB]$ $20*log(V_L/V_R)$	Vout (max) $2*ATAN(A_L(max)/A_R(max))$
-13	0	0,001843	0,07141	38,74660879	31,76467396	3,089986689
-7	0	0,005173	0,02009	3,883626522	11,78474917	2,637559121
-4	0	0,007012	0,01302	1,856816885	5,375381536	2,153563358
-2	0	0,0089	0,0109	1,224719101	1,760729826	1,772133631
0	0	0,01005	0,01005	1	0	1,570796327
2	0	0,0109	0,0089	0,816513761	-1,760729826	1,369459022
4	0	0,01302	0,007012	0,538556068	-5,375381536	0,988029296
7	0	0,02009	0,005173	0,257491289	-11,78474917	0,504033532
13	0	0,07141	0,001843	0,02580871	-31,76467396	0,051605964

TABLE 7. Similar to table 1 for y=0

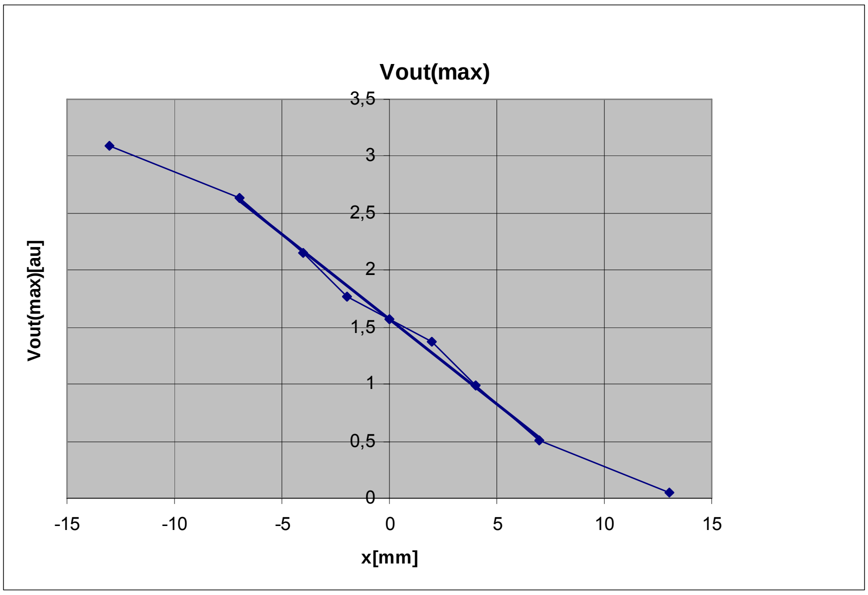

FIGURE 27. $V_{out}(max)$ For Table 7

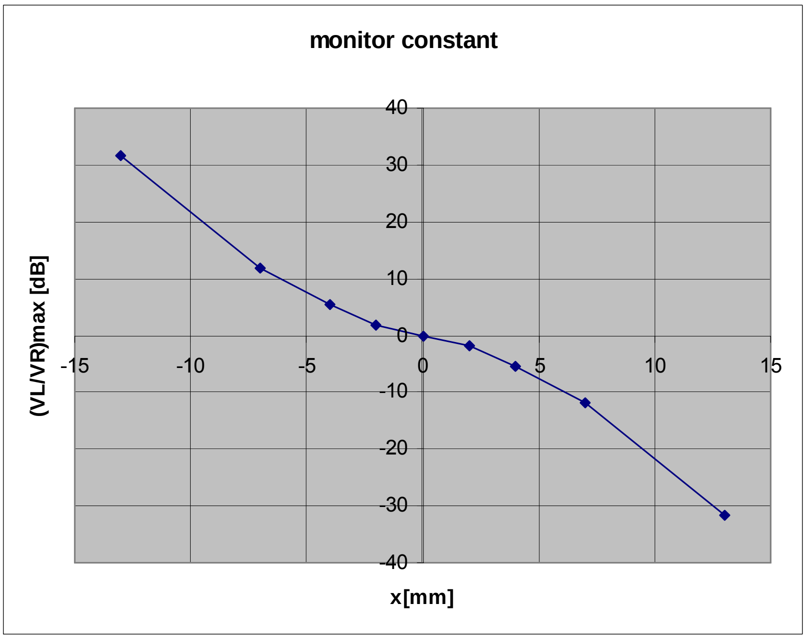

FIGURE 28. V_L/V_R as a function of x for y=0 for the 34 mm stripline BPM

The monitor constant was calculated again with the same method (see previous calculation p.15).

$K = \Delta(V_L/V_R)/\Delta x = 1.25$ [dB/mm]

Characteristic Impedance of Stripline

The characteristic impedance of a stripline is calculated according to [8]

$$Z_{ch} = \sqrt{\frac{L_0}{C_0}} = \frac{\sqrt{\varepsilon\mu}}{C_0}$$

where L_0 is the inductance per unit length
C_0 is the capacitance per unit length
ε is the permitivity
(for vacuum: 8,854e-012 F/m)
and μ is the permability
(for vacuum: 4πe-012 H/m)

We calculate the capacity similarly to the case of the button BPMs and normalize it to the length of the stripline.

$C_0 = 13.7$ [pF/mm]
$Z_{ch} = 48.84$ [Ω/m]

5.2. 44 mm Stripline BPM

The 44mm stripline BPM has the same design as the 34mm stripline, with the following dimensions: stripline radius is 22 mm, channel radius is 8.49 mm, and the length is 200 mm. The results of the simulations are given in table 8 and figure 29.

Beam offset		**V_R**	**V_L**	**$(V_L/V_R)(max)$**	**$(V_L/V_R)(max)[dB]$**	**Vout (max)**
x	**y=0**	**$A_R(max)$**	**$A_L(max)$**		**$20*log(V_L/V_R)$**	**$2*ATAN(A_L(max)/A_R(max))$**
-8	0	0,007404	0,02172	2,933549433	9,347868217	2,484531309
-4	0	0,009136	0,01692	1,852014011	5,352885356	2,151399342
0	0	0,01273	0,01274	1,000785546	0,006820487	1,571581564
4	0	0,01692	0,009136	0,539952719	-5,352885356	0,990193312
8	0	0,02172	0,007404	0,340883978	-9,347868217	0,657061344

TABLE 8. Similar to table 1 for y=0

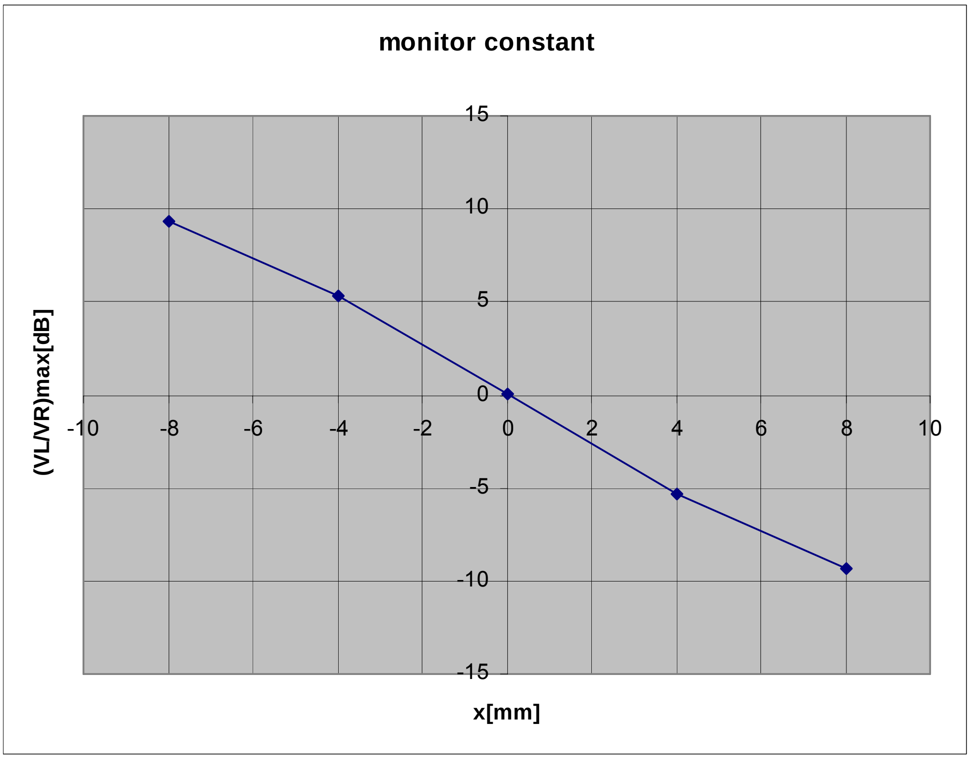

FIGURE 29. V_L/V_R as a function of x for y=0. for the 44 mm stripline BPM

The monitor constant is
$K = \Delta(V_L/V_R)/\Delta x = 1.34$ dB/mm.

6. SUMMARY

The FLASH button and stripline BPMs have been analyzed in this study. CST programs were used. Various monitor characteristics have been obtained.
These results of this work are important to check the design values of these monitors and will be used in analyzing the signals measured from these monitors, as for example for their calibration.

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