



Characterization of the Bunch Compressor Beam Position Monitor for FLASH 2

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Abstract

The goal of this project was to simulate and characterize a button Beam Position Monitor (BPM) to be placed in the bunch compressor section of the FLASH 2 beamline. This will assist in the energy stabilization of the beam by providing the position of the beam and calculating its energy spread in the bunch compressor. A parametric study of the button was conducted to get the optimum design. The design of the BPM is finalized based on the signal strength in the frequency range of the read-out electronics. The monitor constant of the BPM was also computed in the simulation by moving the beam in both the transverse directions. Two methods were used for this computation and the method of alternate buttons is found to be better.

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1 Introduction

Accelerators increase the energy of a beam of charged particles using electromagnetic fields and control it using magnetic fields [1]. In this acceleration process, ideally, the beam should be located at the center of the beam pipe. This is achieved and sustained with the help of focusing devices like dipole magnets [3]. However, the beam trajectory could be offset from the center due to a variety of reasons [2]. Thus, Beam Position Monitors (BPMs) are an essential component of accelerator facilities. They are non-destructive diagnostic tools used to measure the transverse position of the beam (centre of charge) with respect to the chamber axis. There are various kinds of BPMs based on geometry, design and operation methods. The principal goal of a BPM is to measure the signal generated due to the electromagnetic field of the beam.

In this project, I worked on the characterization of a button BPM which will be installed in the bunch compressor section of the FLASH 2 beamline.

1.1 FLASH

FLASH is a free-electron laser (FEL) operating since 2005. It produces ultra-short X-ray pulses (shorter than 30 femtoseconds) using the Self-Amplified Spontaneous Emission (SASE) [7] process. The electron bunches are produced in a laser-driven photoinjector and then accelerated by a superconducting linear accelerator.

These electron bunches are longitudinally compressed so that the peak current increases. This is achieved by first accelerating them on the falling slope of the RF wave, then passing them through a magnetic chicane which consists of dipole magnets [5]. In this arrangement, the electrons with lower energy which are the ones ahead in the bunch take a longer detour and the trailing electrons with higher energy take the shorter path. So at the exit of the bunch compressor, the electron bunches are compressed.

FLASH 1 has fixed gap undulators while FLASH 2 has variable gap undulators. The electrons interact with the magnetic field of the undulators and form micro bunches that radiate intense coherent X-ray pulses. The FLASH layout is shown in Fig. 1.

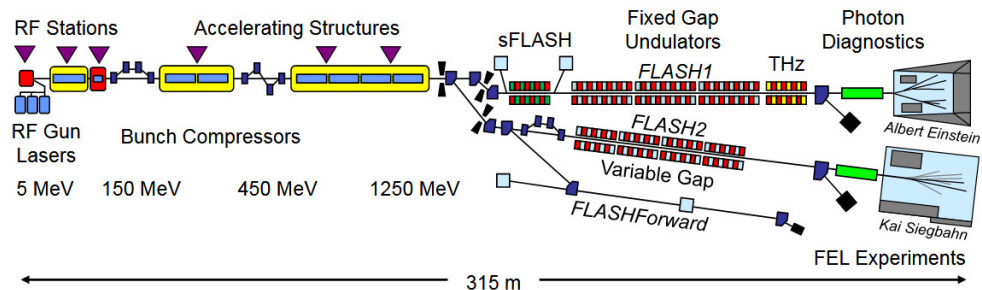


Figure 1: Schematic layout of FLASH

The SASE process is driven by high brightness electron beams. The accelerator gives a range of 350 MeV to 1.25 GeV electron energies that provides a wavelength output of 52 to 4 nm.

2 Theory

2.1 Beam Position Monitors

BPMs are standard diagnostic devices in accelerators measuring bunched beams. The antennas of a button BPM are installed at the beam pipe wall and they pick up the signal induced due to the electromagnetic field of the passing beam (See Fig. 2). The coupling further is done using rf technologies.

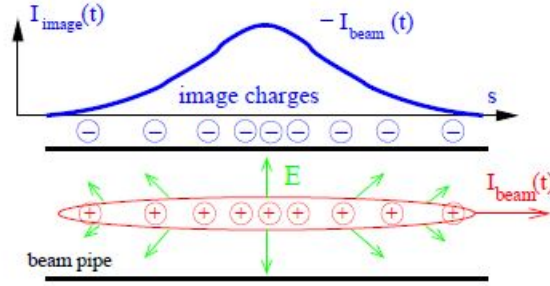


Figure 2: Beam induced wall current [6]

The electrodes are installed on opposite sides of the chamber or beam pipe (Fig. 3) and the difference of the signals from these opposite plates give the centre of charge of the beam with respect to the centre of the beam pipe. The beam position is extracted by comparing the voltages

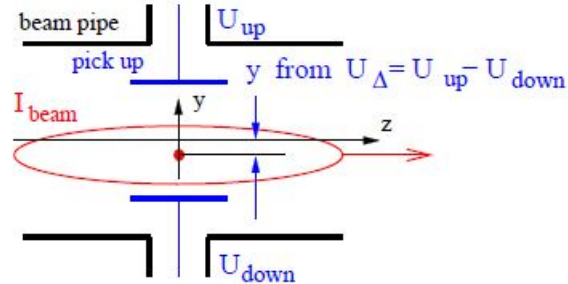


Figure 3: Beam displacement calculation [6]

picked up in the horizontal or vertical directions.

Beam Position Measurement

The beam position is calculated from the voltage amplitudes. For capacitive coupling, like in the case of button BPMs, the ‘difference over sum’ method is employed.

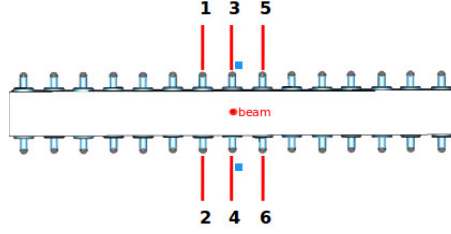


Figure 4: Planar arrangement of the buttons on the chamber wall

For the arrangement shown in Fig. 4, Q_x in the horizontal plane is calculated as,

$$Q_x = \left\{ \frac{(U_{leftup} + U_{leftdown}) - (U_{rightup} + U_{rightdown})}{(U_{leftup} + U_{leftdown} + U_{rightup} + U_{rightdown})} \right\} \quad (1)$$

where U is the voltage amplitude measured by the BPM,

$$S_x = \frac{dQ_x}{dx} \quad (2)$$

S_x is the position sensitivity of the BPM. It is defined as the response of the BPM to the offset of the beam.

$$k_x = \left(\frac{dQ_x}{dx} \Big|_{dQ_x/dx=max} \right)^{-1} \quad (3)$$

k_x is defined as the monitor constant and this value is used to determine the beam offset in the horizontal plane during the beam operation. In the case of y offset, the displacement in the vertical plane,

$$Q_y = \left\{ \frac{(U_{leftup} + U_{rightup}) - (U_{leftdown} + U_{rightdown})}{(U_{leftup} + U_{leftdown} + U_{rightup} + U_{rightdown})} \right\} \quad (4)$$

Further S_y and k_y can be computed just like the horizontal case explained above.

There are two methods to compute Q in the simulation (consider Fig. 4),

1. Method 1 (Adjacent buttons) : When adjacent buttons like the buttons 3,4,5 and 6 are used,

$$Q_x = \left\{ \frac{(U_3 + U_4) - (U_5 + U_6)}{(U_3 + U_4 + U_5 + U_6)} \right\} \quad (5)$$

2. Method 2 (Alternate buttons) : When alternate buttons like the buttons 1, 2, 5 and 6 are used,

$$Q_x = \left\{ \frac{(U_1 + U_2) - (U_5 + U_6)}{(U_1 + U_2 + U_5 + U_6)} \right\} \quad (6)$$

Both these methods are used and compared in the simulations.

In conclusion, if the beam is located exactly in the centre of the beam pipe the amplitude is equal in the pair of pick-ups placed opposite to each other in the same plane. When the beam has an offset in a particular direction, there is a non-uniform distribution of voltage on the antennas. Therefore, the monitor constant is used to reconstruct the beam position.

Button BPM

Button BPMs are used mostly in the cases of short bunches with a frequency range of 100 MHz to 3 GHz. They have a compact structure and a lower cost of installation than other types of BPMs.

Each pick-up antenna is connected to a standard rf-connector outside the vacuum chamber using a short pin. The buttons are usually terminated with an impedance of 50 Ω [2, 6]. The entire structure is designed for maximum transmission of the signal and minimum reflections.

2.2 CST Studio Suite 2019

In order to characterize and optimize the bunch compressor BPM, simulations have been made using the CST Particle Studio Suite 2019. The Wakefield solver [9] is used. It calculates the wake-potentials for a given structure from the electromagnetic fields emitted by a bunched beam of charged particles, by integrating the electromagnetic fields along the z-axis. Fig. 5 shows the wakefields generated due to charge q1 and how it affects the charge q2 behind it at a finite distance s.

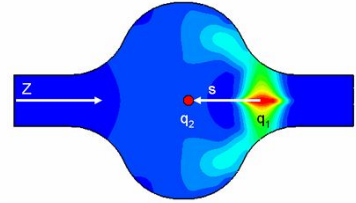
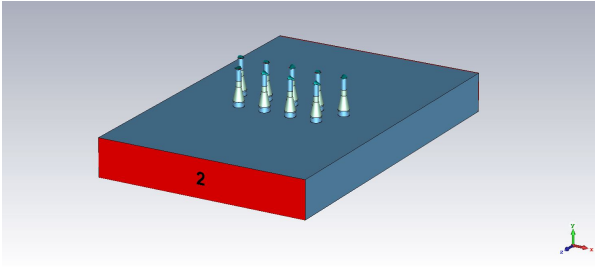


Figure 5: Wakefield [9]

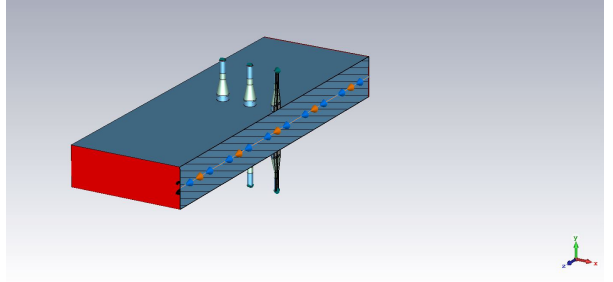
3 Simulations

The BPM was modelled in CST as explained in the following sections. The boundary conditions were set to zero magnetic field thus forbidding electric field perpendicular to the boundary plane in the simulations.

A bunched beam of 0.25 nC charge and $\sigma=5$ mm is implemented. The wakefield integration method is set to indirect testbeam as this offers maximum accuracy for a relativistic beam. The simulations were run over a frequency range of 0-12 GHz.



(a) top-view of BPM



(b) Cross-sectional view of BPM

Figure 6: View of the chamber, buttons and beam

3.1 Chamber design

As shown in Fig. 6 the buttons are placed in two rows on a chamber of dimensions $158 \times 28 \times 240$ mm³. The transverse faces of the chamber through which the beam passes are also set as ports [11] in the simulation so that they are not considered as default Perfect Electric Conductor (PEC) background. Otherwise this could lead to reflections of the bunched beam and give resonant peaks in the signal collected by the BPM.

3.2 BPM Design

The pick-up feedthrough of the button is made of PEC seen in Fig. 7. The conical shape of the pick-up assists in transmitting the signal with minimum loss.

The pick-up is surrounded by an insulating structure (Fig. 9) made of glass (pyrex) loss-free material. The buttons are separated from each other by a distance of 20 mm. The structure of



Figure 7:
Pick-up

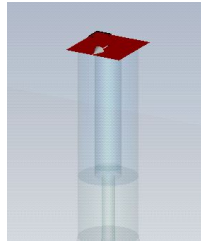


Figure 8: Port

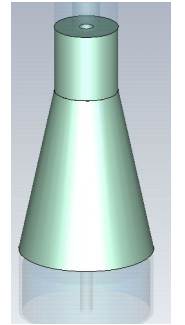
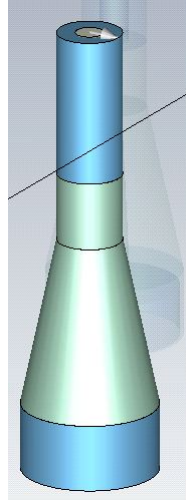


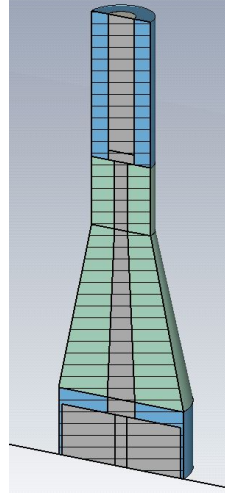
Figure 9:
Pick-up
isolation

an individual button designed in the simulation is given in Fig. 10. The starting design of the button (Fig. 11) has a radius of 3.75 mm and thickness of 3.0 mm. The pick-up has a radius of 0.375 mm. The total height of the BPM is about 26.5 mm.

At the top of the feedthrough a voltage monitor is placed along with a port to measure the voltage. The port (Fig. 8) is equivalent to a perfectly matched load. Waveguide ports are used to feed the calculation domain with power and to absorb the returning power.



(a) 3-D view of the pick-up



(b) Cross-section of the pick-up

Figure 10: Button BPM

The following cases were simulated and studied :

1. Variation of button radius : The radius of the button (Fig. 11) was varied from 3 mm to 3.8 mm. For comparison, the starting design of the button has a radius of 3.75 mm.
2. Variation of button thickness : The button thickness was varied from 1 mm to the standard 3.0 mm keeping the rest of the parameters constant.(Fig. 12)
3. Variation of gap between the button and connector : The gap between the button and the rest of the structure (Fig. 13) is varied from the standard 0.95 mm to 3 mm, keeping the button thickness constant at 3.0 mm.

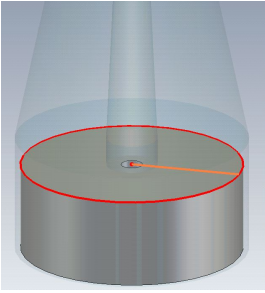


Figure 11: Button radius

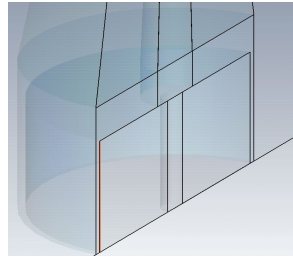


Figure 12: Button thickness

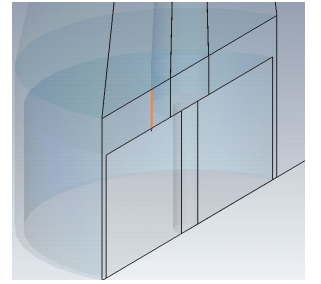


Figure 13: Gap

Now in order to study the position sensitivity and calculate the monitor constant the following parametric study was conducted :

1. Horizontal scan : The y-offset of the beam is set to zero and a horizontal scan of the beam x-offset from -40 to 40 mm is conducted. This is used to calculate the k_x value of the BPM.

2. Vertical scan : The x-offset is set to zero and the y-offset parameter is varied from -12 to 12 mm. This run is used to evaluate k_y .
3. Horizontal scan with a vertical offset : The y-offset is fixed at $y=6$ mm and a horizontal scan is conducted just like the first case.

4 Results

4.1 Voltage measurements

Fig. 14 shows the voltage amplitudes measured by the pick-ups 1 (red), 3 (green) and 6 (blue) which correspond to the positions 0 mm, 20 mm and 40 mm from the beam position. From the

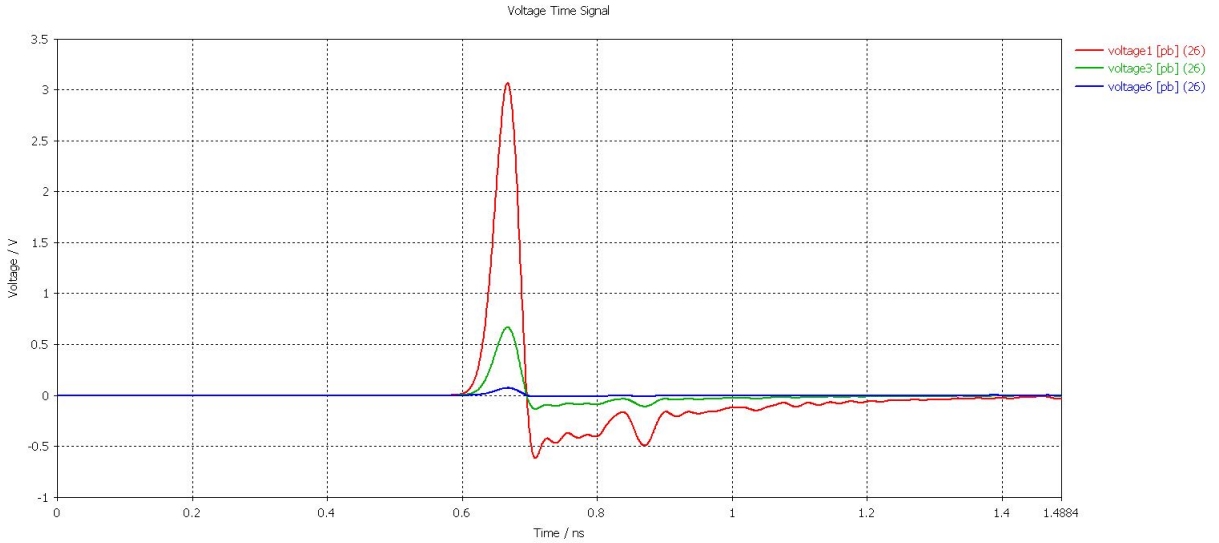


Figure 14: Voltages from different buttons as a function of time

graph, it can be concluded that the voltage amplitude of the signal drops with the increase of the distance of the button from the beam.

The results of the various cases studied are given below :

1. Variation of button radius : The voltage amplitude is measured for various button radii. In the figures 15-18, voltage1(20), (22), (24) and (26) correspond to the button radii 3 mm, 3.2 mm, 3.4 mm and 3.8 mm respectively.
 - (a) Time signal : The beam has zero offsets in both transverse planes. The signal from the pick-ups placed directly above and below the beam are shown in Fig. 15 and 16 respectively.

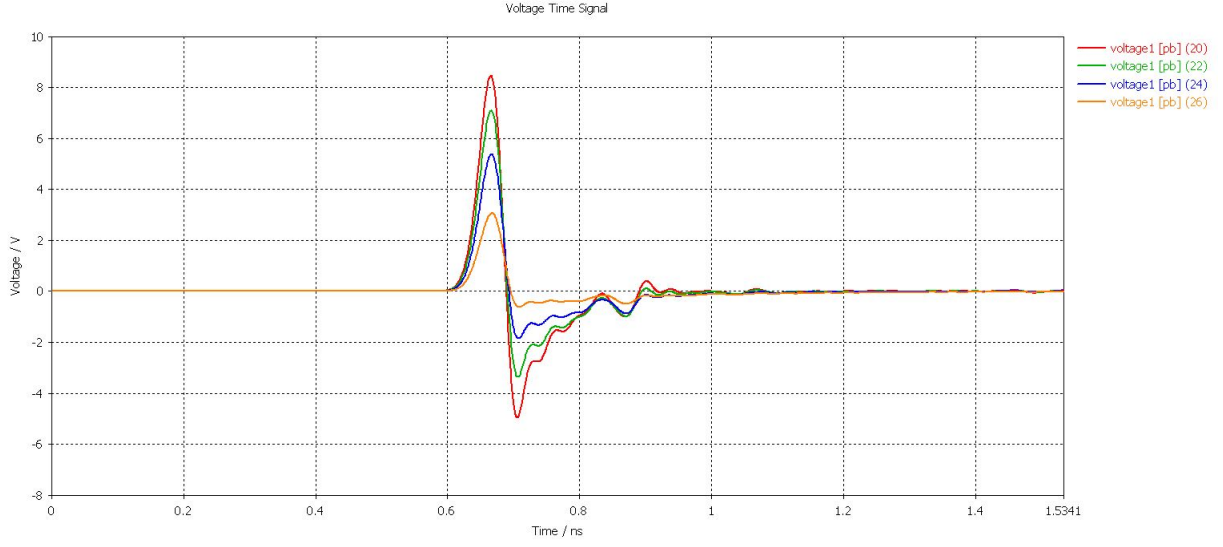


Figure 15: Top center button

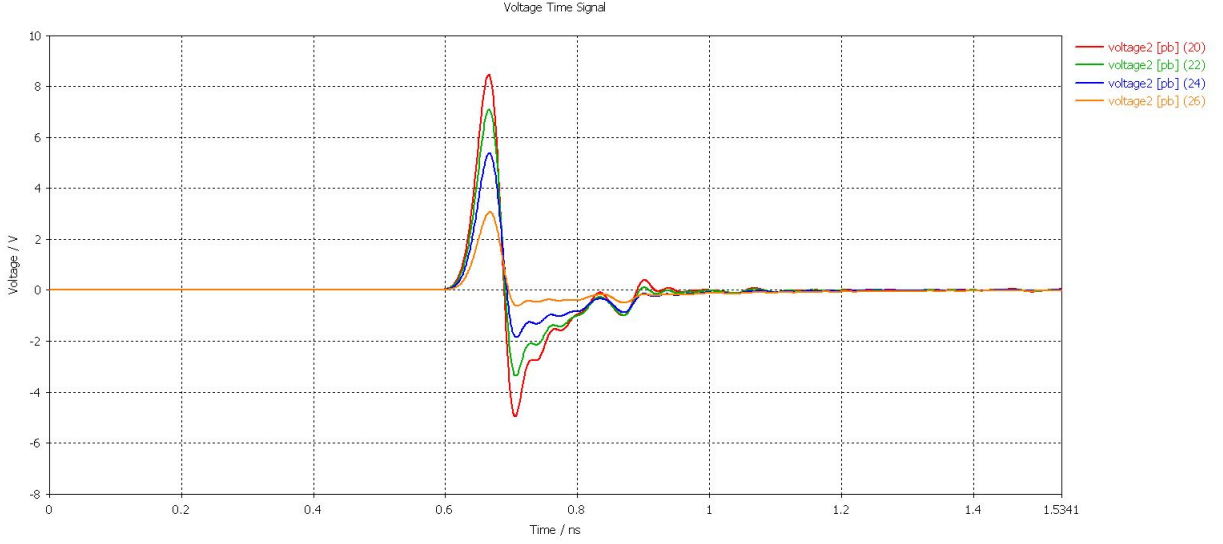


Figure 16: Bottom center button

From the figures 15 and 16 it can be concluded that the buttons directly opposite to each other give the same voltage amplitudes for a particular set of button dimensions and that the voltage drops with larger button radius.

- (b) Frequency signal : Fig. 17 shows the voltage amplitude measured by the top center button (placed directly above the beam bunch) in the frequency domain.

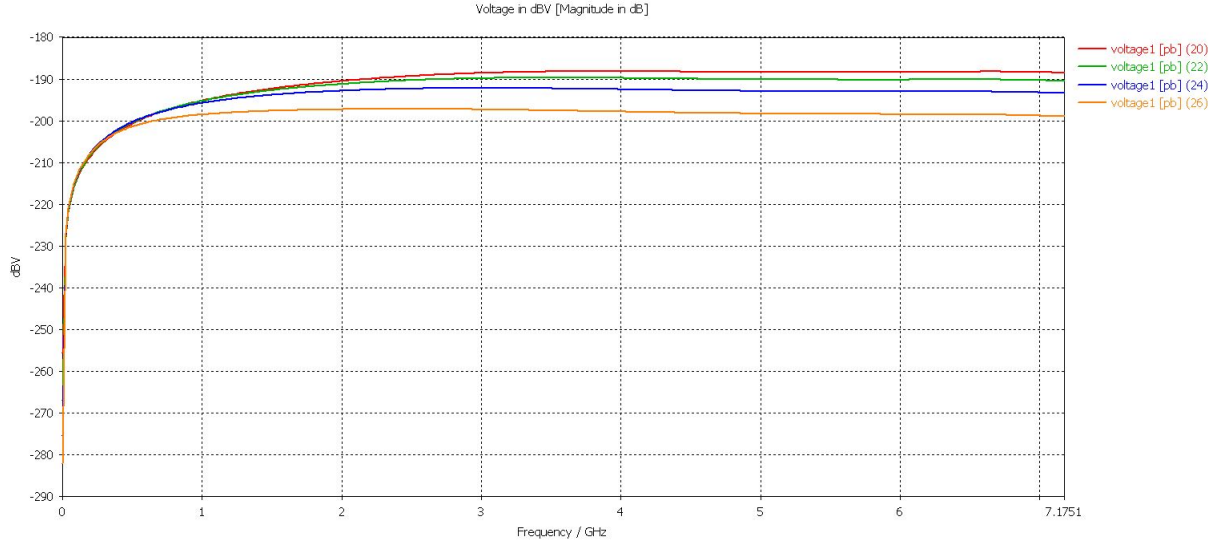


Figure 17: Top center button

From the graph, it is observed that the change in button radius affects the voltage only at very high frequencies. The read-out electronics has a low pass cut off frequency of about 1.5 GHz. Thus, a reduction in radius from the present model would not be useful.

- (c) Low pass filter : The signal is passed through a butterworth low pass filter. The cut-off frequency is set at 1.5 GHz. The filtered signal is shown in Fig. 18.

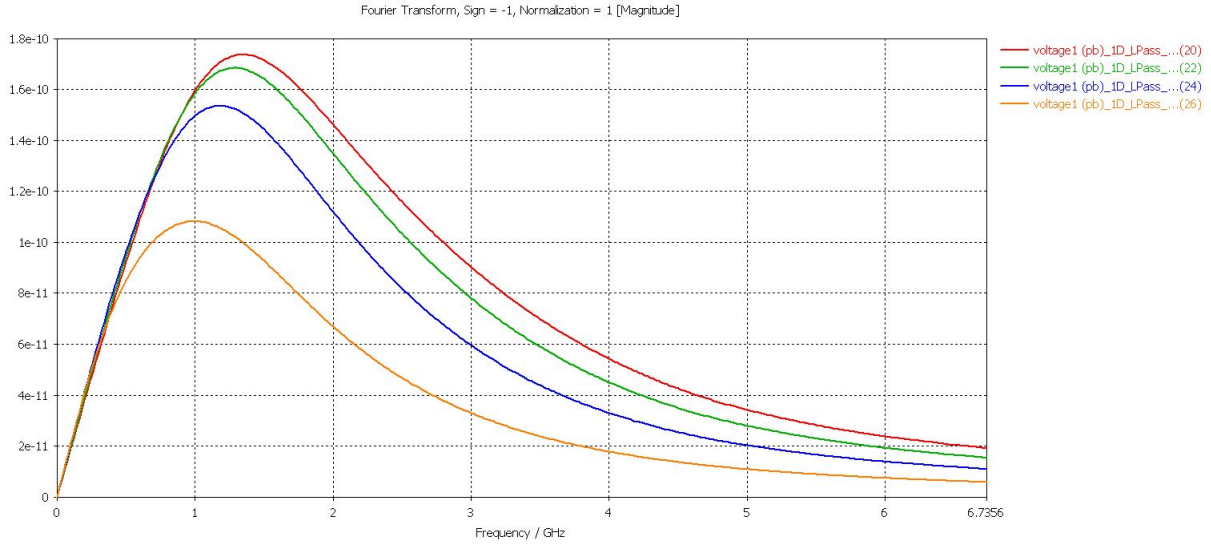


Figure 18: Low pass filtered signal

It is observed from the above graphs that the voltage increases with the reduction of the button radius.

Below (Fig. 19) is a plot of the maximum voltage measured by the top center button as a function of the button radius. This shows that the voltage drops with larger radius.

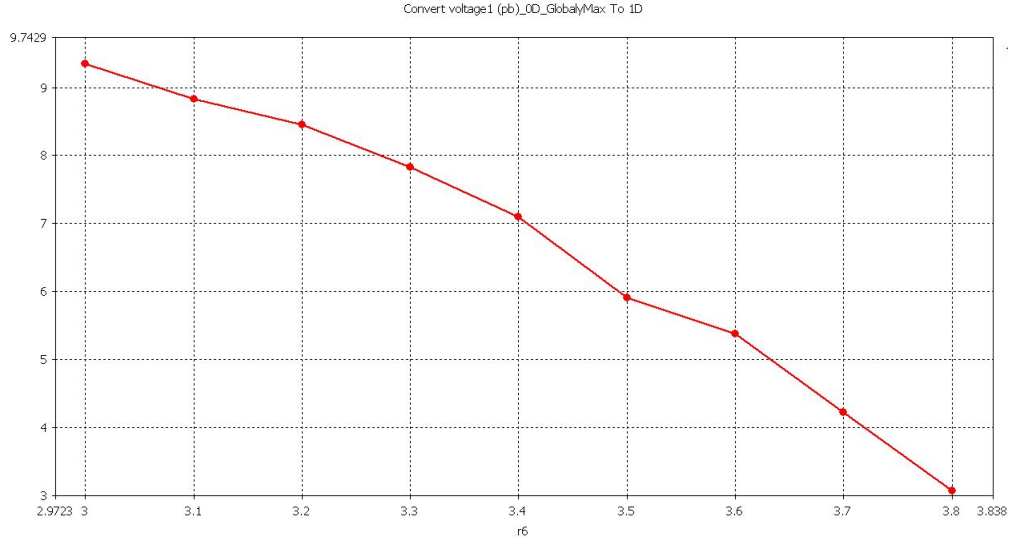


Figure 19: Voltage as a function of radius

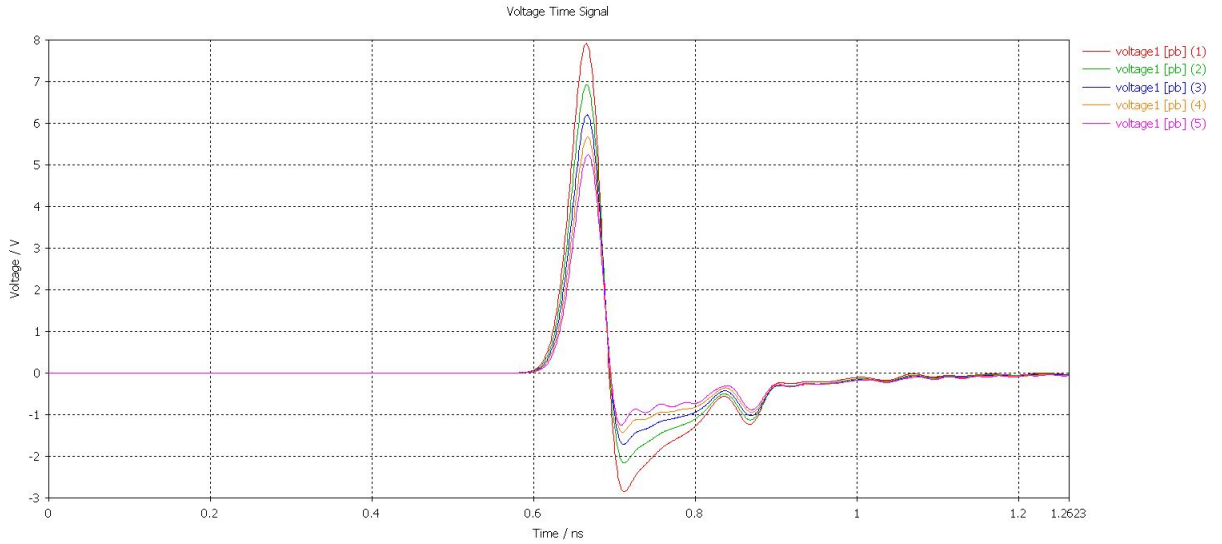


Figure 20: Time signal

2. Variation of button thickness : The button thickness is varied from 1 mm to 3 mm. In the figures 20 and 21, voltage1(1), (2), (3), (4) and (5) correspond to thickness of 1 mm, 1.5 mm, 2 mm, 2.5 mm and 3 mm respectively. Fig. 20 shows that the voltage drops with the increase in button thickness.

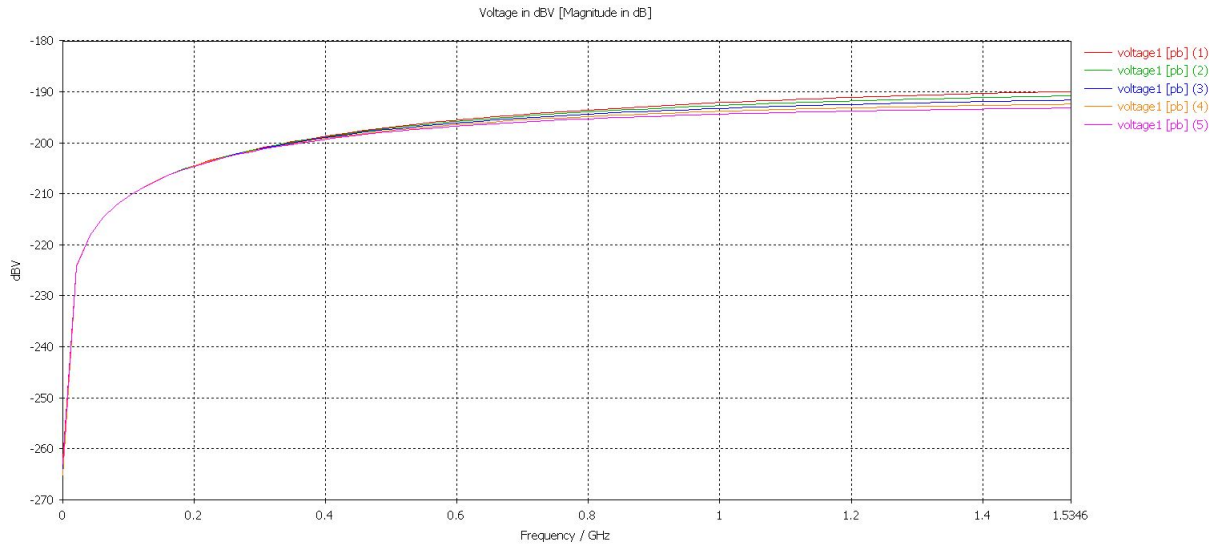


Figure 21: Frequency signal

From Fig. 21 it is observed that there is no visible change in voltage as a function of button thickness at lower frequencies. Fig. 22 shows the change in voltage amplitude as a function

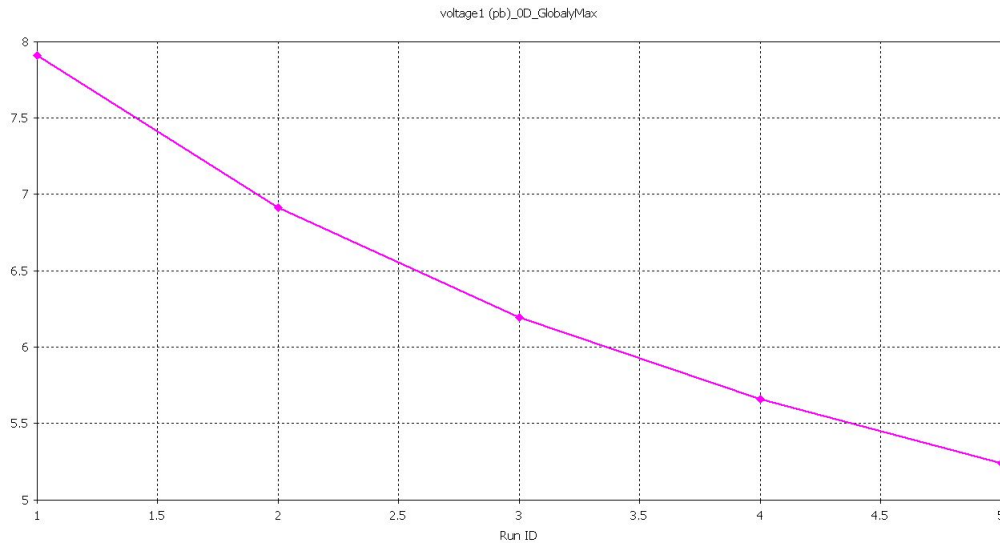


Figure 22: Voltage as a function of button thickness

of button thickness. It can be concluded from this graph that the voltage drops as the button thickness increases.

3. Variation of gap between the button and connectors : In the figures 23 and 24, voltage1(5), (7) and (9) correspond to gaps of 1mm, 2 mm and 3 mm respectively.

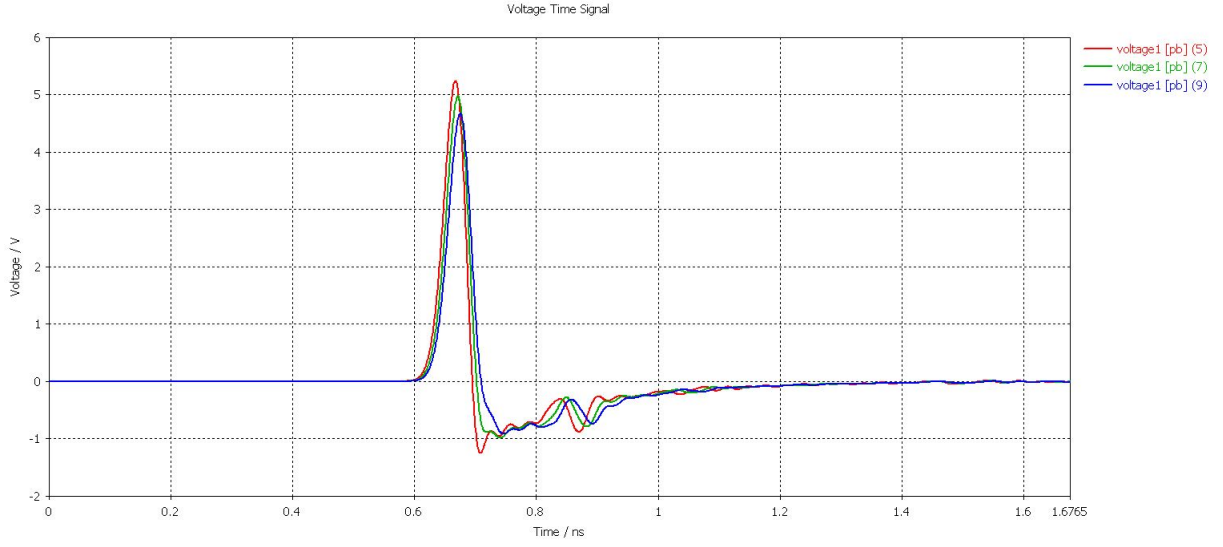


Figure 23: Time signal

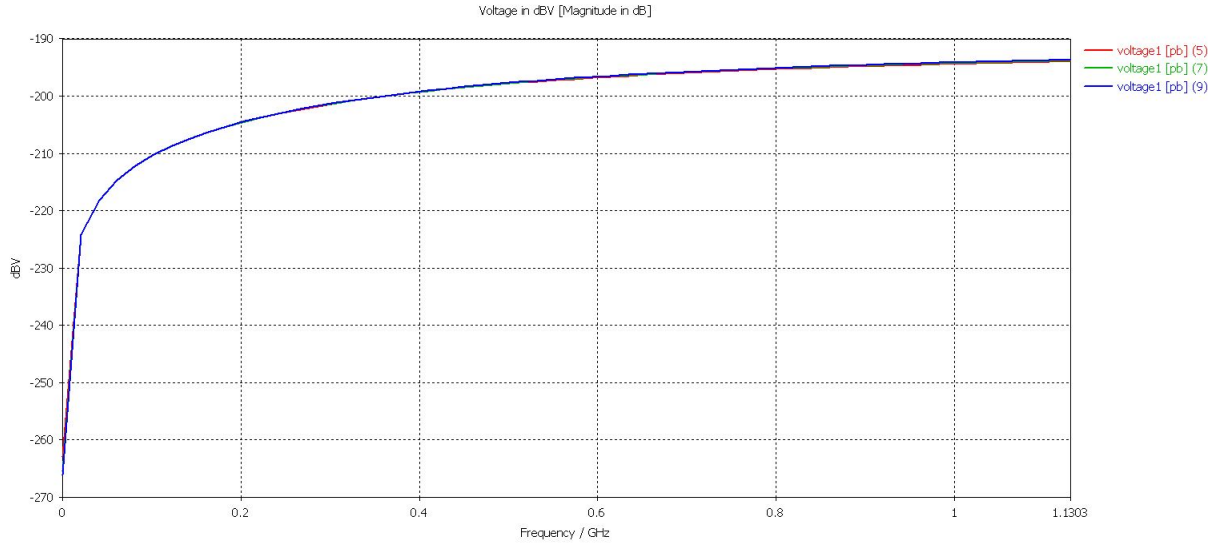


Figure 24: Frequency signal

From the above graphs, it is observed that the voltage drops with the increase in gap but it is not a very significant change.

A comparison of the maximum voltage recorded by the voltage monitor on the top center button with respect to the gap variation is given in Fig. 25. and no significant change of the amplitude is visible.

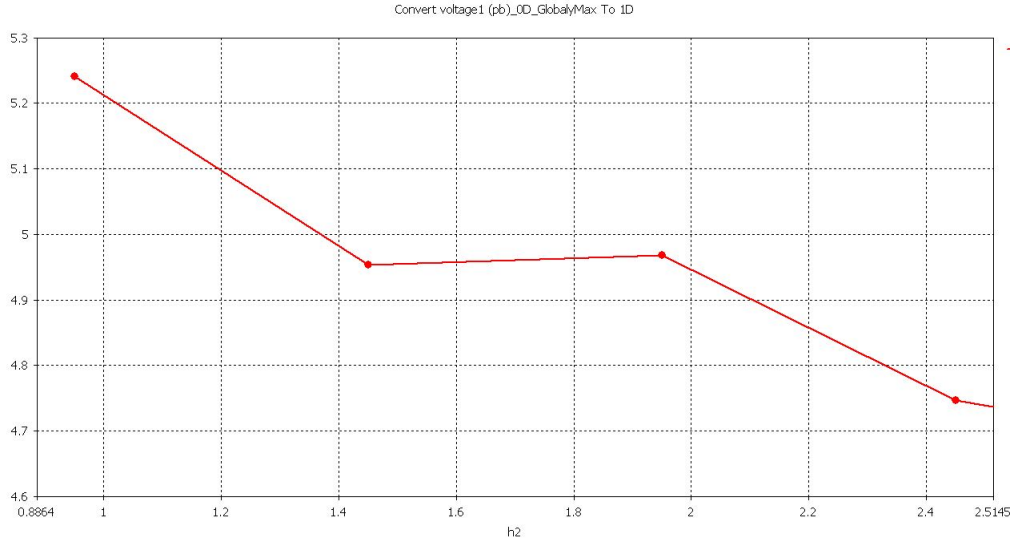


Figure 25: Voltage as a function of button gap

4.2 Monitor constant

The monitor constant is computed in both transverse planes using the ‘difference over sum’ method described earlier.

1. Horizontal scan : The vertical offset is set to zero and a horizontal scan is conducted from -40 mm to 40 mm. Figures 26 and 27 show Q_x as a function of x-offset computed by methods 1 and 2 respectively.

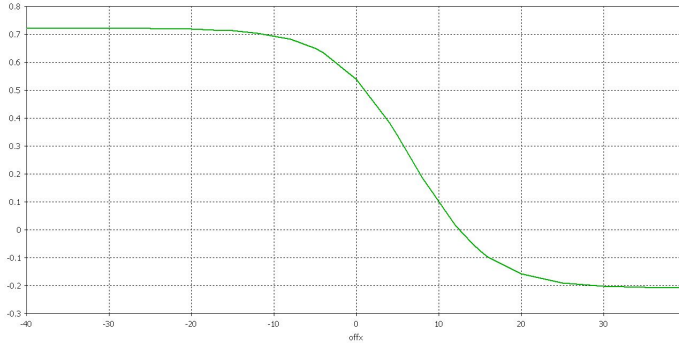


Figure 26: Q_x as a function of x (Method 1)

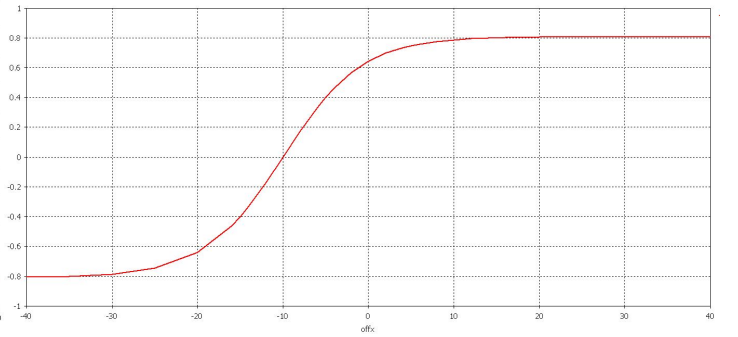


Figure 27: Q_x as a function of x (Method 2)

2. Horizontal scan with a vertical offset of 6 mm : A horizontal scan with a vertical offset of the half thickness of the chamber in y direction (6 mm) is conducted to observe the change in k_x value in the case of a vertically offset beam. Methods 1 and 2 described earlier are employed as seen in figures 28 and 29 respectively. Tables 1 and 2 give the k_x value computed for the cases 1 and 2 described above. The values in each row of the tables correspond to different sets of buttons. It is observed that method 2 gives more consistent values and method 1 is more dependent of the vertical offset.

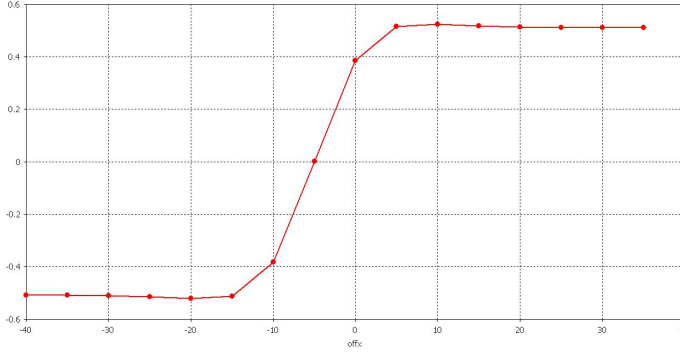


Figure 28: Q_x as a function of x (Method 1)

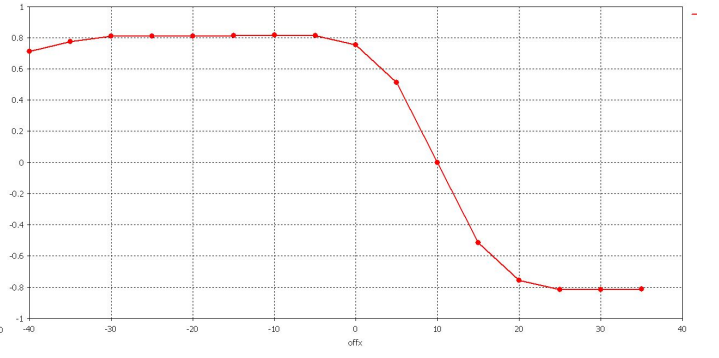


Figure 29: Q_x as a function of x (Method 2)

Table 1: k_x (mm) Method 1
(Adjacent buttons)

y-offset=0 mm	y-offset=6 mm
20.188	13.0228
20.307	15.622
20.1885	13.0243
16.4083	17.8385

Table 2: k_x (mm) Method 2
(Alternate buttons)

y-offset=0	y-offset=6
11.555	9.73
12.177	9.73
11.55	9.73
12.48	9.72

3. Vertical scan : The horizontal offset is set to zero and a vertical scan is conducted from -12 to 12 mm. The k_y computed for the center buttons are :

$k_y=10.3448$ mm (Method 1)

$k_y=10.4214$ mm (Method 2)

Figures 30 and 31 show Q_y determined by methods 1 and 2 respectively.

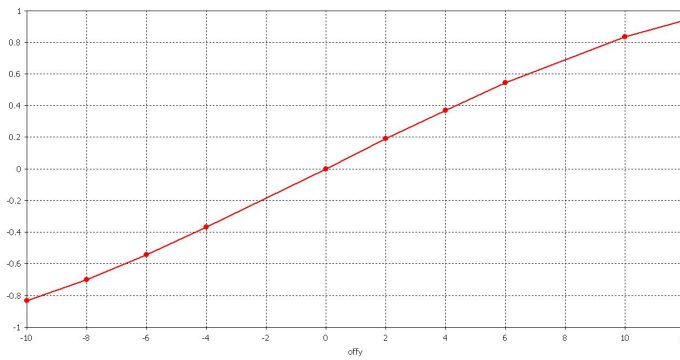


Figure 30: Q_y as a function of y (Method 1)

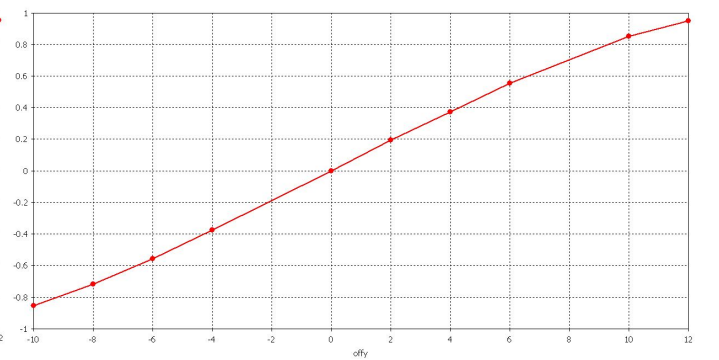


Figure 31: Q_y as a function of y (Method 2)

5 Conclusion

From the studies, it can be concluded that the given button BPM design can be used for the bunch compressor in FLASH 2. The change in parameters like radius, thickness and gap between the button and connectors alter the voltage but not in the frequency range of interest. Thus, a change in design is not recommended.

Further, the results prove that the method of using alternate buttons to compute the monitor constant gives more consistent, vertical offset independent results than the adjacent button method.

Acknowledgement

I would like to thank my supervisors Dr. Dirk Lipka and Dr. Nicoleta Baboi for teaching and guiding me through this internship. The DESY Summer Programme 2019 organizers, Dr. Olaf Behnke and the entire team for making the whole program run so smoothly and efficiently. The DESY International Office deserves a special mention as they guided me through the much important visa procedure with patience. My family and friends make it easy for me to work happily and I am most thankful to them.

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