DESIGN AND SIMULATION OF BUTTON BEAM POSITION MONITOR FOR IR-FEL*

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Abstract

A new button-type beam position monitor (BPM) was designed for the IR-FEL* project. Firstly, the longitudinal size of BPM needs to be short enough to save space because the entire machine of IR-FEL is very compact. And in the matter of installation problem, all four electrodes are deviated 30 degrees from the horizontal axis. Then, according to these two limited conditions and beam parameters, we built up a simple model and did some simulated calculations to ensure a good performance of position resolution, which should be better than 50μm. The simulations include an estimation of induced signals in both time and frequency domains, horizontal and vertical sensitivities, mapping figures and so on. This button BPM will be manufactured in the near future and then we can do some off-line experiments to test it.

INTRODUCTION

The Infrared Free Electron Laser (IR-FEL) project, currently under investigation at NSRL, mainly consists of a pulsed grid controlled electron gun, a prebuncher, a buncher, two linear accelerators, a chicane and beam transport lines.

It is obviously important to develop a complete beam diagnostic system to measure all kinds of beam parameters and guarantee stable machine operation in future. This paper mainly introduces the button-type BPM that would be used in measurement system. Basic beam parameters are presented in Table 1, which are significant for the design and simulation of BPM.

Table 1: Electron Beam Parameters of IR-FEL

Beam energy	30~50MeV
Bunch charge	Q=1nC
Bunch length, rms	σ=2~5ps
Bunch repetition rate	59.5,119,238,476MHz
Macro pulse length	Max:13μs
Macro pulse repetition rate	10Hz

DESIGN

BPM Type Choose

The beam position measurement system requires about ten BPMs throughout the entire machine. Considering the compaction of the machine, the longitude length of BPM is quite limited. At the same time, in consideration of both the low budget outlays and not too strict demand of position resolution (better than 50μm), the most reasonable choice is button-type BPM.

Specific Parameters of BPM

Comprehensively considering installation problems, intensity of induced signals, sensitivity in both directions, response time and so on, some preliminary design parameters of the button BPM are chosen, as listed in Table 2.

Table 2: Design Parameters of Button BPM

Longitude length	25mm
Vacuum chamber radius	b=17.5mm
Electrode thickness	L=1.6mm
Electrode radius	r=5mm
Gap between electrode and vacuum	w=0.3mm
Electrode deviation angle from horizontal axis	ϕ=30 degrees
Coaxial cable impedance	Z=50Ω

SIMULATION

Position Calibration Simulation

According to Table 2, we build a cross-section model of vacuum chamber, as shown in Fig. 1, in which four button electrodes are named A, B, C, and D in clockwise order.

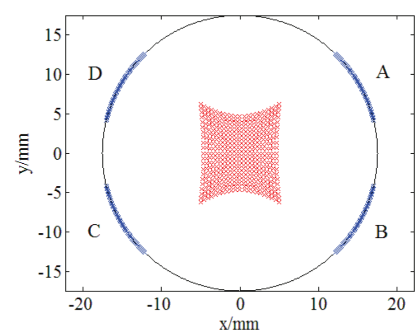

Figure 1: Vacuum chamber definition and Mapping diagram.

Assuming that the beam moves from (-5, -5) mm to (5, 5) mm by a step size of 0.5mm, then we can acquire the induced charges Q_A, Q_B, Q_C and Q_D by boundary element method [1]. The normalized position (U, V) can be calculated through the difference over sum method, which is showed in Eq. (1).

Depending on these 441 groups of data, we can draw the mapping figure (shown in the center of Fig. 1), proceed linear fitting of U and x (or V and y), at the same time get

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more accurate relationship of x (or y) and (U, V) by polynomial fitting.

$$U_{\Delta/\Sigma} = \frac{Q_A + Q_B - (Q_C + Q_D)}{Q_A + Q_B + Q_C + Q_D}$$
$$V_{\Delta/\Sigma} = \frac{Q_A + Q_D - (Q_B + Q_C)}{Q_A + Q_B + Q_C + Q_D} \quad (1)$$

Equation (2) shows the linear fitting results where the horizontal sensitivity coefficient S_x is 0.09248mm^{-1} and vertical sensitivity coefficient S_y is 0.05347 mm^{-1}.

$$U_{\Delta/\Sigma} = 0.09248 \cdot x + 1.211 \times 10^{-17}$$
$$V_{\Delta/\Sigma} = 0.05347 \cdot y + 1.514 \times 10^{-18} \quad (2)$$

Equations (3) and (4) show the third order polynomial fitting formulas while Figs. 2 and 3 display the fitting errors, both of which are in the level of micron.

$$x = -0.0051 + 10.4418U_{\Delta/\Sigma} + 0.0953V_{\Delta/\Sigma} - 0.9009U_{\Delta/\Sigma}{}^2 - 0.8947U_{\Delta/\Sigma}V_{\Delta/\Sigma} - 0.5787V_{\Delta/\Sigma}{}^2 + 5.1827U_{\Delta/\Sigma}{}^3 + 1.8046U_{\Delta/\Sigma}{}^2V_{\Delta/\Sigma} - 7.2008U_{\Delta/\Sigma}V_{\Delta/\Sigma}{}^2 + 1.0846V_{\Delta/\Sigma}{}^3 \quad (3)$$

$$y = -0.0021 + 0.1833U_{\Delta/\Sigma} + 17.8682V_{\Delta/\Sigma} - 1.2812U_{\Delta/\Sigma}{}^2 - 0.2836U_{\Delta/\Sigma}V_{\Delta/\Sigma} - 0.3919V_{\Delta/\Sigma}{}^2 + 2.0432U_{\Delta/\Sigma}{}^3 - 22.0417U_{\Delta/\Sigma}{}^2V_{\Delta/\Sigma} - 3.5908U_{\Delta/\Sigma}V_{\Delta/\Sigma}{}^2 + 20.2843V_{\Delta/\Sigma}{}^3 \quad (4)$$

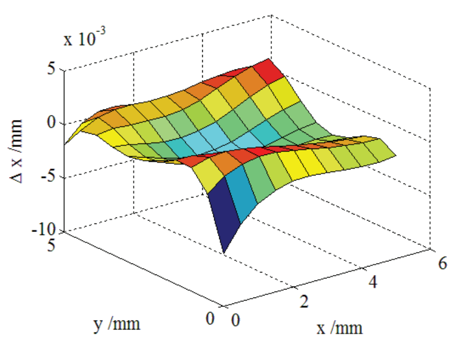

Figure 2: Polynomial fitting error (Δ x vs. x & y).

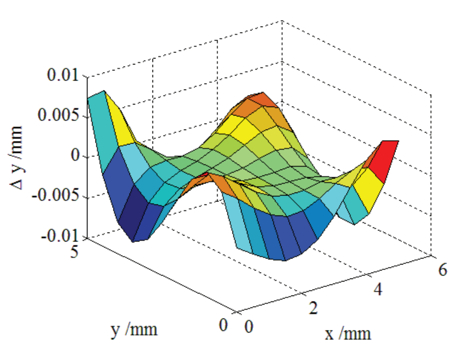

Figure 3: Polynomial fitting error (Δ y vs. x & y).

All these results provide references for the next offline calibration work.

Signal Modeling

In this section, we establish a processing chain, which corresponds to a macro pulse (for a length of 13μs, in which there are a lot of bunches), to follow signal from the beam pipe to the back-end electronics equipment, namely Libera Single Pass E (Libera SPE) [2].

The single bunch current signal is Gaussian distributed in time domain, shown as Eq. (5).

$$I(t) = Q / \left(sqrt(2\pi) \cdot \sigma\right) \cdot \exp\left(-t^2 / 2\sigma^2\right) \quad (5)$$

Then the image current out of button can be gotten through Eq. (6), and the button voltage is the product of the image current and the impedance seen by this current, presented in Eq. (7) and Eq. (8) [3].

$$I_{imag}(\omega) = \left(S_{button} / C_{vacuum}\right) \cdot \left(i\omega / \beta c\right) \cdot I(\omega) \quad (6)$$
$$Z(\omega) = \left(Z^{-1} + i\omega C\right)^{-1} \quad (7)$$
$$V(\omega) = I_{imag}(\omega) \cdot Z(\omega) \quad (8)$$

In Eq. (6), S_{button} means the estimated projection area of button in vacuum chamber and the C_{vacuum} means the circumstance of vacuum cross-section perpendicular to the beam direction. Equation (9) displays the parasitic capacitance between the button and the wall of vacuum.

$$C = 2\pi\varepsilon_0 L / \ln\left((r + w) / r\right) \quad (9)$$

Then the signal arrive Libera SPE via LMR-400 coaxial cable, the calculated attenuation of which is showed as Eq. (10) [4].

$$Att. = (0.12229) \cdot \text{sqrt}\left(F_{MHz}\right) + (0.00026) \cdot F_{MHz} \quad (10)$$

An example is given by making the single bunch length is 5ps. The signals (corresponding to a single bunch inside a macro pulse) in each previous stage are displayed in Figs. 4 and 5, as shown below.

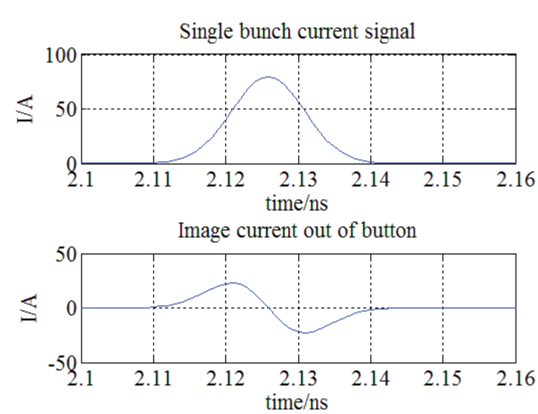

Figure 4: Beam and image current signal vs. time.

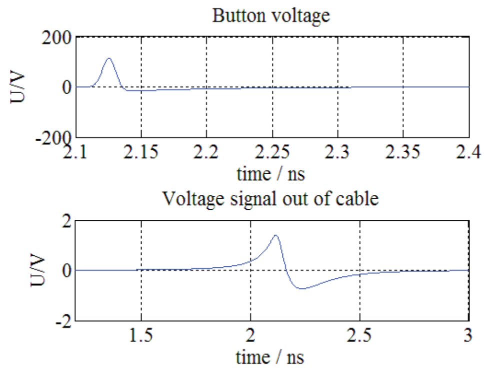

Figure 5: Button voltage and voltage out of cable.

Resolution

According to the signal that entered into Libera SPE, the beam position is calculated using formulas in Eq. (11).

$$X = K_X \cdot \frac{(V_A+V_B)-(V_C+V_D)}{V_A+V_B+V_C+V_D}$$
$$Y = K_Y \cdot \frac{(V_A+V_D)-(V_B+V_C)}{V_A+V_B+V_C+V_D} \quad (11)$$

Thus the amplitude range of the input signal, in a sense, decides the position resolution. Libera SPE brochure draws the relationship of resolution and input signal level (see Fig. 6) [2], from which we can see that the position resolution is better than 50μm while the dBFS (decibels relative to full scale) of final signal is higher than -32.

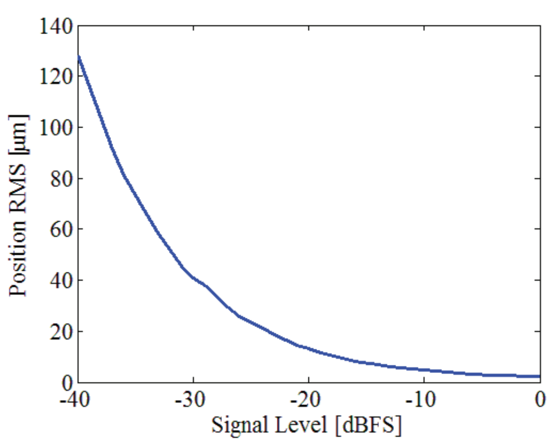

Figure 6: Typical resolution values at different signal levels.

Assuming the maximal displacement of beam is (5, 5) mm, then button-A and button-C will respectively get the maximal and minimal signal, from which we can easily obtain the dBFS of signal.

Figure 7 presents the schematic diagram to calculate the induced signal when the polar coordinates (r, θ) of beam deviate from (0, 0), which differs from beam is in (0, 0) while using Eq. (6).

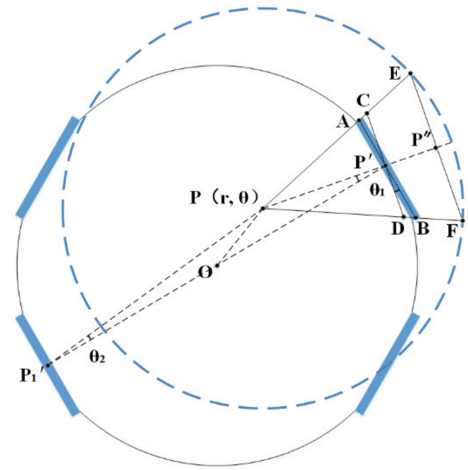

Figure 7: Schematic diagram.

When beam locates in (0, 0), the projection of button electrode in vacuum chamber is just button itself. But when beam is in (r, θ), assuming there is a vacuum chamber (same size as the real one) centered at (r, θ), then the projection should be an ellipse whose long-axis, short- axis and area can all be calculated by Eq. (12).

$$long = 2ab / r_1, \quad short = 2ab\cos(\theta_1)/r_1$$
$$S_{button} = \pi a^2 b^2 \cos(\theta_1)/r_1^2 \quad (12)$$

As shown in Fig. 7, for the electrode nearest to the beam (P), r_1 means the distance from P to the center of electrode (P′) and θ_1 is the angle between PP′ and OP′ (the same principle applies to the other electrodes), both of which can be easily gotten by means of trigonometric function.

According to the above principle, S_x and S_y are calculated as 0.09338mm^{-1} and 0.05319 mm^{-1}, which are approximately equal to the values in Eq. (2). So this principle can be considered as reliable.

Different repetition rates and bunch lengths both have influence on signal amplitude, so all sorts of combination conditions of them should be considered. After careful calculation, the dBFS of signals in all conditions are almost -6, which means resolution is nearly 8μm.

CONCLUSION

A new button-type BPM for IR-FEL was presented in this paper. Some simulations were done to obtain BPM parameters such as sensitivities. And a simple processing chain to follow signal from the beam pipe to the back-end electronics equipment was introduced, which shows the resolution of this BPM is greatly better than 50μm.

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