Design and simulation of a beam position monitor for the high current proton linac*

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Abstract In this paper, the 2-D electrostatic field software, POISSON, is used to calculate the characteristic impedance of a BPM (beam position monitor) for a high current proton linac. Furthermore, the time-domain 3-D module of MAFIA with a beam microbunch at a varying offset from the axis is used to compute the induced voltage on the electrodes as a function of time. Finally, the effect of low β beams on the induced voltage, the sensitivity and the signal dynamic range of the BPM are discussed.

Key words beam position monitor, characteristic impedance, sensitivity, low β

PACS 29.20.Ej

1 Introduction

Proton radiography provides a unique capability for the study of dynamic processes using the proton beam and a magnetic lens imaging system. Because protons interact through both the strong nuclear force and the electromagnetic force, transmission measurements allow simultaneous imaging and determination of material properties with very high time resolution. This special feature can be applied as a proton computed tomography for cancer therapy and a hydrotest for nuclear weapon research.

For high current proton accelerators, beam loss control is a key issue. There are some theoretical studies on beam loss but only a handful of experimental studies. By using an already built high-intensity RFQ at IHEP, we can experimentally study the key technologies of beam loss and beam halo. For this purpose, beam diagnostics technology need to be developed. Some BPMs are planned to be installed in the beam line following the RFQ. The beam position monitor will provide information about both the transverse position of the beam and the beam phase that can be used to detect energy on line using the TOF method for the RFQ. The beam parameters of the RFQ are presented in Table 1.

Table 1. Beam parameters of the RFQ.

ion	H+
kinetic energy	3.54 MeV
β	0.083
pulse current	45 mA
RF frequency	352.2 MHz

2 Mechanical design of the BPM

It was decided to choose a 4-electorde BPM design having stripline electrodes with one end shorted. A model of the BPM consists of a cylindrical enclosure with 4 electrodes on a beam pipe, as shown in Fig. 1. The electrodes are flush with the beam pipe and the design only uses four connectors, and since the remaining four are all on one end, the BPM can be mounted inside the quadrupoles magnets.

The BPM will also serve as a beam phase detector with a broadband frequency response. If the BPM matches the sum mode, it is sufficient for the proposed narrow-band signal processing at the linac bunch repetition frequency $f_{\rm b}$ = 352.2 MHz. For the broad-band signal processing including higher harmonics, matching to the dipole mode would be advantageous[1].

Received 4 July 2008

* Supported by NSAF (10576006)

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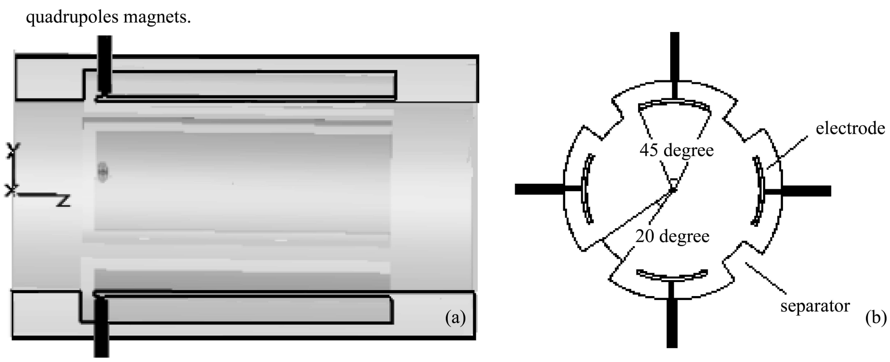

Fig. 1. (a) The stripline BPM with one end shorted; (b) cross section of the BPM. The electrodes are 45 degree and the separators between them are 20 degree.

According to the 4-electrode BPM geometry, there are four independent modes, namely a sum, a vertical dipole, a horizontal dipole and a quadrupole mode. Since the geometry is symmetrical, the impedance of the vertical dipole mode is equal to that of the horizontal dipole mode $Z_{\rm vert}=Z_{\rm horz}$. To obtain the broad-band frequency response, the constraining equation that needs to be satisfied is:

$$R_0=\sqrt{Z_{\rm sum}Z_{\rm quad}}=\sqrt{Z_{\rm vert}Z_{\rm horz}}=Z_{\rm dipole}\ . \qquad (1)$$

So the impedance of dipole mode should be matched to 50 Ω. The value of $\sqrt{Z_{\rm sum}Z_{\rm quad}}$ is also needed to be 50 Ω. If there is no coupling between electrodes, the value would be 50 Ω. For this reason, a separator between the adjacent electrodes is introduced in our design, as shown in Fig. 1(b). The separator is a longitudinal metal ridge placed in the gap between the adjacent electrodes and it reduces the coupling as shown in Fig.2. However it is also noticed in Fig. 2 that the separator decreases the signal power level while it reduces the electrode coupling. In Fig. 2, S13 is a scattering parameter that represents the signal power induced form an electrode, and S34, S35 are the scattering parameters that represent the coupling between adjacent and opposite electrodes, respectively.

The other advantage of using the separator is related to machining imperfections. If the coupling between the electrode is small, the effect of machining imperfections on the matching of the characteristic impedance will be small[1)].

Optimized with a series of the POISSON computations, the design with 45 degree electrodes and 20 degree separators is determined, as shown in Fig. 1. The characteristic impedance of this structure is 53.79 Ω in sum mode, 49.99 Ω in dipole mode, and 48.61 Ω in quadrupole mode, so the value of $\sqrt{Z_{\rm sum}Z_{\rm quad}}$ is equal to 51.13 Ω. It is hard to achieve the value of $\sqrt{Z_{\rm sum}Z_{\rm quad}}$ to be 50 Ω, because it is impossible to eliminate the coupling of the BPM.

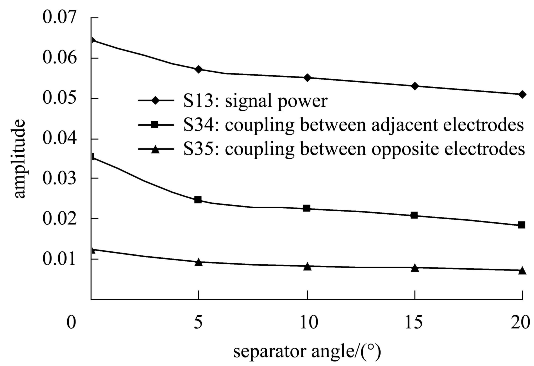

Fig. 2. The signal of the electrode, the coupling between adjacent and opposite electrodes versus the separator angle for a 45 degree BPM.

The largest signal in the frequency domain can be obtained from the electrode, if the length of the electrode is equal to $l=\dfrac{(2n+1)\lambda}{4}$, $n=0,1,2,3,\cdots$. When $n=0$, the length of the electrode is equal to 1/4 of the wavelength of the linac RF frequency, the fundamental harmonic Fourier components of the signal on the electrode will be largest. As we know, the space for beam instrument is so tight that sometimes we have to shorten the length of the electrodes and meanwhile we must keep the signal power high enough. By making a compromise, the length of the 1/8 wavelength of 106 mm is chosen. The mechanical parameters of the BPM are listed in Table 2.

Table 2. Geometrical parameters of the BPM.

beam-pipe(electrode inner) radius	37.5 mm
electrode enclosure box inner radius	47.1 mm
electrode thickness	1.5 mm
electrode length	106 mm
electrode angle for matching	45 degree
separator angle	20 degree

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3 MAFIA simulation result and analysis

The time domain transmission functions of the BPMs are simulated with MAFIA[2] because MAFIA can take beams as excitation sources. A Gaussian longitudinal charge distribution of the bunch with total charge Q=0.1277 nC, and RMS length σ=5 mm is taken to simulate a 45 mA beam in the T3 module of MAFIA for the RFQ. Unfortunately, the time-domain code T3 at present can only simulate the BPM model for ultra relativistic (β=1) beams. In the next section, the ultra relativistic MAFIA results will be used to derive results for β<1.

To study the sensitivity and linearity of the BPM, the simulations with the beam bunch passing through the BPM at different transverse positions were performed. Some results for the BPM are presented in Table 3. $A_{\rm T}$, $A_{\rm B}$, $A_{\rm R}$ and $A_{\rm L}$ are the fundamental harmonic Fourier components of the signals on the top, bottom, right and left electrodes of the BPM, respectively. $A_{\sum}$ represents the sum of the Fourier components of the four electrodes at the fundamental frequency.

Table 3. Amplitudes of signal fundamental harmonics on the BPM electrodes versus beam position.

beam position	@352.2 MHz				
$(x/r,y/r)$	$A_{\rm T}$/V	$A_{\rm B}$/V	$A_{\rm R}$/V	$A_{\rm L}$/V	$A_{\sum}$/V
(0,0)	0.24565	0.24565	0.24565	0.24565	0.9826
(0.125,0)	0.23951	0.23951	0.30626	0.19734	0.98262
(0.25,0)	0.22434	0.22434	0.37471	0.16232	0.98571
(0.375,0)	0.19658	0.19658	0.47844	0.12886	1.00046
(0.5,0)	0.16156	0.16156	0.61662	0.10254	1.04228
(0.125,0.125)	0.29802	0.19271	0.29802	0.19271	0.98146
(0.25,0.125)	0.27748	0.18113	0.36373	0.15854	0.98088
(0.25,0.25)	0.3362	0.14906	0.3362	0.14906	0.97052
(0.375,0.125)	0.24004	0.15984	0.46305	0.12572	0.98865
(0.375,0.25)	0.28615	0.13158	0.42406	0.11778	0.95957
(0.375,0.375)	0.35206	0.10302	0.35206	0.10302	0.91016
(0.5,0.125)	0.19329	0.13271	0.59583	0.09972	1.02155
(0.5,0.25)	0.2241	0.10914	0.54158	0.092551	0.967371
(0.5,0.375)	0.26266	0.08385	0.43655	0.079023	0.862083
(0.5,0.5)	0.30185	0.061068	0.30185	0.061068	0.725836

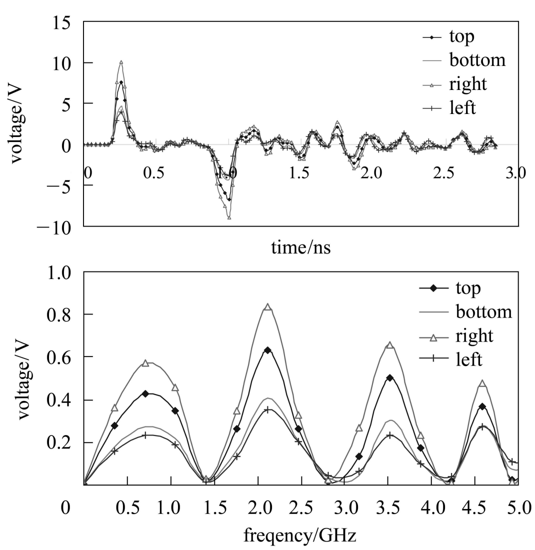

Fig. 3. Signals on four BPM electrodes from a passing transversely displaced ($x=r/4, y=r/8$) bunch: the upper — voltages versus time during one period $T=1/f=2.839$ ns; the bottom — normalized Fourier transform amplitudes (V) versus frequency.

Table 3 shows that $A_{\sum}$ (sum signal) is equal to a constant within a few beam offset. So the amplitude of the sum signal can be used to detect the beam current or beam charge. Fig. 3 shows the voltage on all four electrodes versus time for the case of a beam displaced from the chamber axis by $(x=r/4, y=r/8)$ and their corresponding Fourier transforms.

The sensitivity of the stripline BPM for log ratio can be expressed[3] as

$$S\approx\frac{160}{\ln(10)}\frac{\sin(\varphi/2)}{\varphi\cdot r_{\rm b}}\ , \tag{2}$$

where $r_{\rm b}$, φ are the electrode inner radius and the angle of the electrode, respectively. Taking $r_{\rm b}$ = 37.5 mm, $\varphi=\pi/4$ into Eq. (2), the theoretical position sensitivity value of the BPM is equal to 0.9 dB/mm for the log ratio. The sensitivity value deduced from the MAFIA data is 0.81 dB/mm and it is quite consistent with the theoretical sensitivity value.

In Fig. 4, MAFIA data for the horizontal signal log ratio $\ln(A_{\rm R}/A_{\rm L})/2$ or the difference-over-sum

$(A_\mathrm{R}-A_\mathrm{L})/(A_\mathrm{R}+A_\mathrm{L})$ for the same vertical beam position ($y=0$) show that the log-ratio processing has a better linearity than the difference-over-sum processing. That is why more and more BPM electronics chooses the log ratio processing.

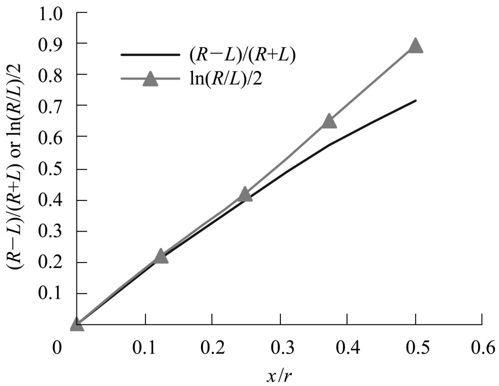

Fig. 4. Horizontal ratio S of the signal harmonics at 352.2 MHz (top line for $S=\ln(A_\mathrm{R}/A_\mathrm{L})/2$, bottom one for $S=(A_\mathrm{R}-A_\mathrm{L})/(A_\mathrm{R}+A_\mathrm{L})$ versus the beam horizontal displacement x/r, for the same vertical beam displacement $y/r=0$.

4 The low beta effect

Since MAFIA can only simulate the BPM model for ultra relativistic (β=1) beams, the effect of the low beta beam needs to be analyzed.

As we know, at a very high energy the EM field of a charge becomes a TEM wave. The relativistic velocity factor β of the exiting beam of the RFQ is equal to 0.083 according to the kinetic energy of 3.54 MeV, as shown in Table 1. At this low velocity, the EM field of a particle in a conducting beam tube is no longer a TEM wave, but has a finite longitudinal extent. The net effect is to reduce the coupling of the high-frequency Fourier components of the beam current to the BPM electrodes, which modifies both the BPM sensitivity to the beam displacement and the signal power of the BPM.

The signals on the BPM electrodes with inner radius r_b and subtended angle φ can be calculated by integrating induced currents within the electrode's angular extent. For a pencil beam bunch passing the BPM at the transverse position $x=r\cos\theta$, $y=r\sin\theta$ at velocity $v=\beta c$, the signals[4] are:

$$
\begin{aligned}
R(f,r,\theta) &= C\frac{\varphi}{2\pi}\left[\frac{I_0(gr)}{I_0(gr_\mathrm{b})}+\frac{4}{\varphi}\sum_{m=1}^{\infty}\frac{1}{m}\frac{I_m(gr)}{I_m(gr_\mathrm{b})}\sin(m\varphi/2)\cos(m\theta)\right],\\
T(f,r,\theta) &= C\frac{\varphi}{2\pi}\left[\frac{I_0(gr)}{I_0(gr_\mathrm{b})}+\frac{4}{\varphi}\sum_{m=1}^{\infty}\frac{1}{m}\frac{I_m(gr)}{I_m(gr_\mathrm{b})}\sin(m\varphi/2)\cos(m(\theta-\pi/2))\right],\\
L(f,r,\theta) &= C\frac{\varphi}{2\pi}\left[\frac{I_0(gr)}{I_0(gr_\mathrm{b})}+\frac{4}{\varphi}\sum_{m=1}^{\infty}\frac{1}{m}\frac{I_m(gr)}{I_m(gr_\mathrm{b})}\sin(m(\pi+\varphi/2))\cos(m\theta)\right],\\
B(f,r,\theta) &= C\frac{\varphi}{2\pi}\left[\frac{I_0(gr)}{I_0(gr_\mathrm{b})}+\frac{4}{\varphi}\sum_{m=1}^{\infty}\frac{1}{m}\frac{I_m(gr)}{I_m(gr_\mathrm{b})}\sin(m(\pi+\varphi/2))\cos(m(\theta-\pi/2))\right],
\end{aligned} \tag{3}
$$

where R, T, L, B are the Fourier components at frequency f of the signals on the right, top, left and bottom electrodes of the BPM, respectively. Here $I_m(z)$ are the modified Bessel functions of the first kind, $g=\dfrac{2\pi f}{\beta\gamma c}$ depends on the frequency, velocity and energy of the beam. The coefficient C depends on the bunch current and shape.

The formulae depend on beta, and we need to fit them with the MAFIA computation results for β=1 listed in Table 3 and then derive results for $\beta<1$ analytically. The best fit to the numerical data in Table 3 was obtained with the effective parameters, $r_\mathrm{eff}=1.1r_\mathrm{b}$, $\varphi_\mathrm{eff}=1.24\varphi$ (=55.8°), C=1.582 and where r_b=37.5 mm, $\varphi=45°$ are the geometrical values. It should be understood that the analytical model that uses these formulae is an approximation to a real BPM. The model assumes an axisymmetric beam pipe and integrates the surface current within the (effective) electrode azimuthal angle to get the signal. In real BPMs, there are gaps and the electrode edges, so certainly each electrode collects more current than within its azimuthal angle.

Figure 5 illustrates that the signal power reduces with the beam energy for a given BPM radius. By varying the beam displacement in a few offsets from the center, the reduction signals values of the four electrodes become different.

Let us focus on our case of β=0.083 (3.54 MeV) and compare the data to β=1 below. The power level for the center beam is reduced by about 20 dB compared to β=1, as shown in Fig. 5. By varying the beam displacement range in $(-r/2, r/2)$, both vertically and horizontally, the strongest signal is reduced by 8.5 dB, and for the weakest one by 26.5 dB compared to the β=1 case. As a result, the dynamical range of the 352.2 MHz signal shifts from about 21 dB for β=1 to about 39 dB at β=0.083. Adding 20 dB due to the current range form 5 mA to 50 mA, the total dynamic range is 59 dB.

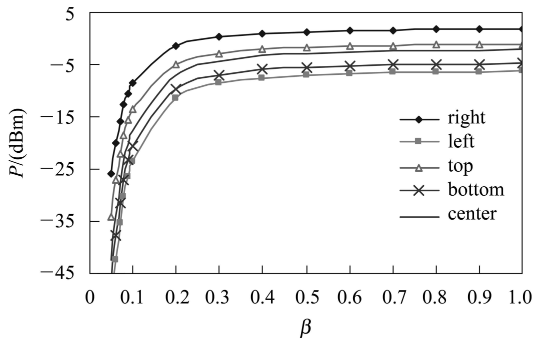

Fig. 5. Power of 352.2 MHz signals on four BPM electrodes versus the beam velocity for beam transverse position: $x=r/4$, $y=r/8$.

The sensitivity of the BPM is given[5] by:

$$S \approx \frac{160}{\ln(10)}(1+G)\frac{\sin(\phi/2)}{\phi b}\ , \tag{4}$$

where $G=0.139\left(\dfrac{\omega b}{\beta\gamma c}\right)^2-0.0145\left(\dfrac{\omega b}{\beta\gamma c}\right)^3$ depends on the frequency, velocity and energy of the beam, and for $\beta\rightarrow1$, $G\rightarrow0$, the Eq. (4) goes over into Eq. (2). It is shown that the nominal BPM response for β=1 is about 0.9 dB/mm in Fig. 6. For 3.54 MeV protons at 352.2 MHz, the sensitivity rises to about 1.7 dB per mm. And it is obvious that for low proton energies the sensitivity reduces with a decrease of the frequency.

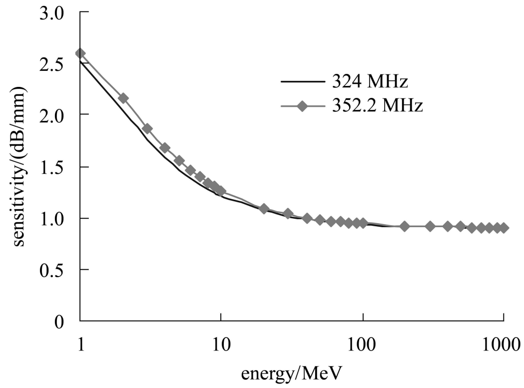

Fig. 6. The sensitivity for a 37.5 mm inner radius, 45 degree wide BPM versus energy for protons bunched at 324 MHz and 352.2 MHz.

5 Summary

Based on the POISSON 2-D electrostatic field computations, the design optimization of the beam position monitor for the RFQ has been done, and the design with 4 one-end-shorted 45 degree electrodes and 20 degree separators was chosen. Furthermore, according to the results obtained from the MAFIA data, it has been shown that the BPM can provide good linearity and sufficient signal power for position and beam phase measurements.

With respect to the case of the low beta beam we concluded: (1) The signal power of the electrode is reduced for lower beam energies. (2) The signal dynamic range increases with decreasing particle velocity. (3) The sensitivity increases with a decrease of the beam energy.

We plan to fabricate a BPM model that will be used with the RFQ this year, so that we can test the model on line, and further improvement of the performance is being studied.

We would like to thank Zhou Demin, Cheng Yi, Professor Cao Jianshe and Professor C. Deibele for their helpful suggestions.

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