ANALYSIS AND CALCULATION OF BEAM ENERGY SPREAD MONITOR FOR HLS LINAC*

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Abstract

The energy spread measurement using the energy spectrum analysis system at HLS LINAC now is an intercepting measurement which can't measure the real injection beam. To achieve the non-intercepting measurement, a new Beam position monitor (BPM) with eight stripline electrodes in four-axis symmetry is designed, which can measure the energy spread at HLS LINAC in real time. This paper has introduced the physical structure of this new BPM which include eight 20 degree opening angle, 1/4 wavelength (26.2mm) length Stripline electrodes in detail, analyzed and calculated the electrode response and picking up the quadrupole component, and got the theoretical sensitivities of different methods. The BPM is simulated and calculated by CST Microwave Studio Program. The results shows the parameters such as characteristic impedance, electrode coupling degree, time-domain response and frequency-domain response etc are all meet the requirement of HLS LINAC and transfer line.

INTRODUCTION

The energy spread of beam is one of the important parameters of Linac. The energy spread measurement using the energy spectrum analysis system at HLS LINAC now is an intercepting measurement which can't measure the real injection beam. To achieve the non-intercepting measurement, a new beam energy spread monitor (BESM) with eight stripline electrodes in four-axis symmetry is designed, which can measure the energy spread at HLS LINAC in real time. The obvious advantage of it to the traditional eight-electrode beam energy spread monitor in eight-axis symmetry as KEKB is that the data processing later is more simply.

BESM SIGNAL

The schematic of new BESM is shown in Fig. 1. The distance between electrodes and BPM center is given by b, and their opening angle by $\phi=(\alpha_1-\alpha_2)/2$. And the inside radius of BESM is given by a. Consider an infinitely long line current $I(r,\varphi)$ at radial location r and azimuthal angle φ. The image current density $j(r,\varphi,a,\theta)$ on a conducting circular cylindrical pipe of radius a at azimuthal angle θ is then[1]:

$$j(a,\theta,r,\varphi)=\frac{I(r,\varphi)}{2\pi a}\frac{a^2-r^2}{a^2+r^2-2ar\cos(\theta-\varphi)} \\ =1+2\sum_{n=1}^{\infty}(r/a)^n\cos[n(\theta-\varphi)] \quad (1)$$

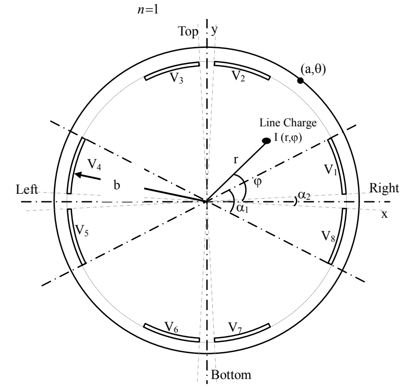

Figure 1: Schematic of the new beam energy spread monitor.

For a gaussian distribution beam $I_{beam}(r,\varphi)$, we assumed (x_0,y_0) is the beam centre, and σ_x, σ_y are the RMS half widths in the x and y directions. Here, $x_0=r\cos\varphi$, $y_0=r\sin\varphi$, and σ_x, $\sigma_y \ll a$. And we assume there is no coupling between x and y directions in the beam. For a total beam current I_{beam}, integrating (1) over r and φ with this gaussian distribution, we can get :

$$j(a,\theta)=\iint j(a,\theta,r,\varphi)drd\varphi=\frac{I_{beam}}{2\pi a} \\ \times\left\{\begin{array}{l} 1+2\left(\frac{x_0}{a}\cos\theta+\frac{y_0}{a}\sin\theta\right) \\ +2\left(\frac{\sigma_x{}^2-\sigma_y{}^2+x_0^2-y_0^2}{a^2}\cos 2\theta+2\frac{x_0y_0}{a^2}\sin 2\theta\right) \\ +2\left(\begin{array}{l}\frac{3\sigma_x{}^2-3\sigma_y{}^2+x_0^2-3y_0^2}{a^2}\frac{x_0}{a}\cos 3\theta \\ +\frac{3\sigma_x{}^2-3\sigma_y{}^2+3x_0^2-y_0^2}{a^2}\frac{y_0}{a}\sin 3\theta\end{array}\right) \\ +2\left[\begin{array}{l}\frac{3\left(x_0^2-y_0^2+\sigma_x{}^2-\sigma_y{}^2\right)^2-2x_0^4-2y_0^4}{a^4}\cos 4\theta \\ +\frac{4x_0y_0(x_0^2-y_0^2+3\sigma_x{}^2-3\sigma_y{}^2)}{a^4}\sin 4\theta\end{array}\right] \\ +\text{higher order terms}\end{array}\right\} \quad (2)$$

In fact, this gaussian restriction is not necessary [2]. Consider BESM that consists of eight pickup stripline electrodes, as shown in Fig.1, here $b\approx a$. Integrating the equation (2) over respective θ, we can get the signal of each stripline electrode.

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RESULTS OF PICK UP σ_X^2-σ_Y^2

Usually, two methods are used to pick up the second moment σ_x^2-σ_y^2 from BPMs' signals, which are the difference/sum ratio (Δ/Σ) method and the log-ratio method [3].

Difference/sum Ratio Method

For Δ/Σ method, we get:

$$\begin{aligned} Q_{\Delta/\Sigma} &= \frac{V_R+V_L-V_T-V_B}{V_R+V_L+V_T+V_B} \\ &= 2\frac{\sin\alpha_1-\sin\alpha_2}{\alpha_1-\alpha_2}\left(\frac{\sigma_x^2-\sigma_y^2}{b^2}+\frac{x_0^2-y_0^2}{b^2}\right)+O\left(\frac{1}{b^6}\right) \end{aligned} \tag{3}$$

Here, $V_R=V_1+V_8$, $V_T=V_2+V_3$, $V_L=V_4+V_5$, $V_B=V_6+V_7$.

While omit 3rd order, we approximately get:

$$\begin{cases} P_{x,\Delta/\Sigma} = \dfrac{V_R-V_L}{V_R+V_L} \approx 4\dfrac{\sin\dfrac{\alpha_1}{2}-\sin\dfrac{\alpha_2}{2}}{\alpha_1-\alpha_2}\dfrac{x_0}{b} \\ P_{y,\Delta/\Sigma} = \dfrac{V_T-V_B}{V_T+V_B} \approx 4\dfrac{\sin\dfrac{\alpha_1}{2}-\sin\dfrac{\alpha_2}{2}}{\alpha_1-\alpha_2}\dfrac{y_0}{b} \end{cases} \tag{4}$$

We can solve x_0, y_0 from the equation (4), and then take the result into the equation (3), we get the second moment σ_x^2–σ_y^2.

The sensitivity of Δ/Σ method is:

$$S_{Q,\Delta/\Sigma} = 2\frac{\sin\alpha_1-\sin\alpha_2}{\alpha_1-\alpha_2}\frac{1}{b^2} \tag{5}$$

Log-ratio Method

According to

$$\ln(1+x) = x-\frac{x^2}{2}+\frac{x^3}{3}-\frac{x^4}{4}+\frac{x^5}{5}+\cdots(-1<x\le 1) \tag{6}$$

For log-ratio method, we can get:

$$\begin{aligned} Q_{\ln} &= \ln\frac{V_RV_L}{V_TV_B} = 8\frac{\sin\alpha_1-\sin\alpha_2}{\alpha_1-\alpha_2} \\ &\times\left\{\frac{\sigma_x^2-\sigma_y^2}{b^2}+\left[1-\frac{2\left(\sin\dfrac{\alpha_1}{2}-\sin\dfrac{\alpha_2}{2}\right)^2}{(\alpha_1-\alpha_2)(\sin\alpha_1-\sin\alpha_2)}\right]\frac{x_0^2-y_0^2}{b^2}\right\} \\ &+O\left(1/b^4\right) \end{aligned} \tag{7}$$

In the same way, we approximately get:

$$\begin{cases} P_{x,\ln} = \ln\dfrac{V_R}{V_L} \approx 8\dfrac{\sin\dfrac{\alpha_1}{2}-\sin\dfrac{\alpha_2}{2}}{\alpha_1-\alpha_2}\dfrac{x_0}{b} \\ P_{y,\ln} = \ln\dfrac{V_T}{V_B} \approx 8\dfrac{\sin\dfrac{\alpha_1}{2}-\sin\dfrac{\alpha_2}{2}}{\alpha_1-\alpha_2}\dfrac{y_0}{b} \end{cases} \tag{8}$$

The sensitivity of log-ratio is:

$$S_{Q,\ln} = 8\frac{\sin\alpha_1-\sin\alpha_2}{\alpha_1-\alpha_2}\frac{1}{b^2} \tag{9}$$

SENSITIVITY

According to the principle of measure energy spread by use multi-strip electrodes detector, we must put the energy spread monitor at the high dispersive part. And generally it was installed after the bending magnet on the transfer line.

In order to avoid direct the synchrotron radiation light irradiation on the stripline electrodes of BESM, the gap angle α_2 has a minimum value [4]:

$$\alpha_{2,\min} = 2\arcsin\left(\frac{3\sigma_y}{R_{el}}\right) \tag{10}$$

Here, σ_y is the beam envelope on the y direction which direction without dispersion, R_{el} is the radius of stripline electrodes. For the NSRL LINAC, $\sigma_y\approx 1$mm, $R_{el}\approx 21.5$mm， $\alpha_{2,\min}\approx 16^0$.

Fig. 2 has shown the change of the log-ratio method's sensitivity with α_1 and α_2 when $\alpha_1=45\sim70^0$， $\alpha_2=15\sim30^0$. We can find the sensitivity is greater as both α_1 and α_2 are smaller.

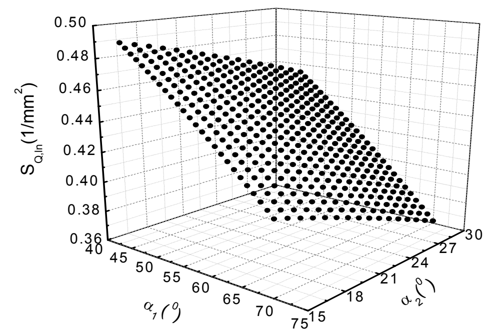


Figure 2: The change of the log-ratio method's sensitivity with α_1 and α_2 .

BESM DESIGN

To determine the BESM of the parameters, we need synthetically consider the time domain response, impedance matching, coupling between the electrodes, sensitivity, etc [5].

Time Domain Response

As shown in Fig. 3, the stripline electrodes can be seen as a part of the transmission with certain characteristic impedance, which's center conductor face to the beam.

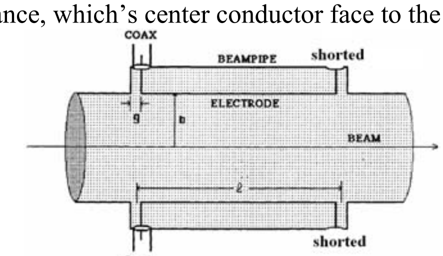


Figure 3: Schematic diagram of stripline electrodes.

When the beam $I_b(t)$ go through the upper of the vacuum chamber in the center, the induced voltage got from the upstream of the stripline electrodes is:

$$V_U(t) = \frac{\phi Z}{4\pi}\left[I_b(t)-I_b\left(t-\frac{2l}{c}\right)\right] \tag{11}$$

In addition to be matched by characteristic impedance, the downstream port is shorted. According to the transmission line theory, it will engender standing waves. And the voltage signal has maximum values at a distance of downstream port 1/4, 3/4, 5/4 etc. times of the wavelength. We choose band 1/4 times of the wavelength, and the electrode's length is 26.2mm.

Impedance Matching

As the characteristic impedance of transmission cable, general adapter connectors and equipments are all 50Ω, to ensure impedance match, the characteristic impedance of BESM must be 50Ω too.

The characteristic impedance between stripline electrode and the tube wall can be approximatively calculated by microstrip line method as [6]:

$$\begin{cases} Z_0 = \dfrac{120\pi}{W_e/h + 1.393 + 0.667\ln\left(W_e/h + 1.4444\right)} \\ \dfrac{W_e}{h} = \dfrac{W}{h} + \dfrac{t}{2\pi}\left(1 + \ln\dfrac{2h}{t}\right) \end{cases} \quad (12)$$

Which, Z_0 is the characteristic impedance, W for the electrode width, h is the distance between electrode and the tube wall, t for the electrode thickness, W_e is the electrode's equivalent width when $t \neq 0$.

The inside radius of BESM tube wall is 25mm, so the distance $h=25-r-t$, electrode width $W=(r+t)\phi$. Obviously, the characteristic impedance Z_0 is the function of the electrode inside radius r and the electrode thickness t, and the electrode opening angle ϕ. When any three of them are known, another could be figured out. Fig. 4 has shown the relationship between the electrode angle and the electrode inside radius when $t=1.5mm$, $Z_0=50\Omega$.

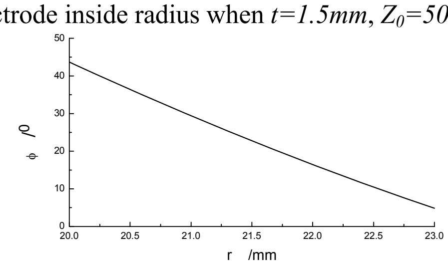
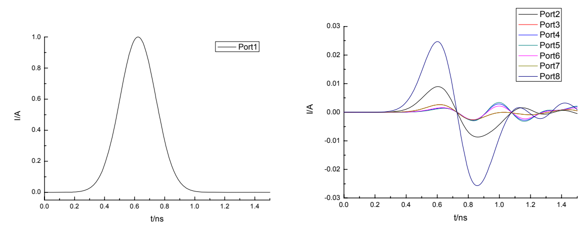


Figure 4: Relationship between the electrode angle and the electrode inside radius.

According to the sensitivity calculation before, we know that both α_1 and α_2 are the small the better, and α_2 has a minimum value 16^0. But when the electrode opening angle is decrease, the signal power got from BESM is lower. So considering the various factors, we choose α_1 as 56^0 and α_2 as 16^0, and the electrode opening angle $\phi=20^0$. According to Fig.6 we can get the electrode inside radius $r=21.7mm$.

Coupling Between Electrodes

According to the designed physical structure, the BESM is simulated and calculated by CST Microwave Studio software. Set a driving current signal source in port 1 as shown in Fig. 5 (a), we can get the response current signals of other ports as shown in Fig. 5 (b). Then we can figure out the coupling coefficients of each two electrodes as shown in Tab.1. Although K_{18} is somewhat big, it will be eliminated in the calculation later because $V_R=V_1+V_8$.



(a) (b)

Figure 5: The current signal of each port.

Table 1: Coupling coefficients

Coupling coefficient	**K_{12}**	**K_{13}**	**K_{14}**	**K_{15}**	**K_{16}**	**K_{17}**	**K_{18}**
Percent %	0.89	0.27	0.30	0.35	0.26	0.27	2.55

CONCLUSION

After synthetically consider the sensitivity of pick up σ_x^2-σ_y^2, the time domain response, impedance matching, the signal power etc., the physical structure of this new BESM which include eight stripline electrodes with 20^0 opening angle, 26.2mm length, 1.5mm thickness, and 21.7mm inside radius is fixed on. After simulated by CST Microwave Studio software, the parameters are all meet the requirement of HLS LINAC.

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