SINGLE PASS COLLIDER MEMO

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TITLE: A NOTE ON IMPROVING THE DESIGN OF THE
HEM₁₁ MODE BEAM POSITION MONITOR*

Introduction

The HEM₁₁ wave BPM presented in^{1,2} has many advantages. It uses actual accelerator cavities to monitor beam position and does not occupy additional space on the beam line. Also it directly monitors beam position within the accelerating section.

Calculations indicate that the HEM₁₁ BPM has high sensitivity. It can be used in the colliding region of SLC as an independent device for monitoring beam position with accuracy on the order of micrometers. In this application it is possible to optimize the design of the HEM₁₁ mode BPM, and make it more effective and even smaller.

When a bunch with charge q passes through an accelerating section at a distance r off axis, the beam-induced energy deposited in the HEM₁₁ mode ($m = 1$) per cavity is:³

$$U = K r^2 q^2 \quad (1)$$

The coefficient K is related to structure parameters and the operating frequency. There are the following formulas:

$$K = \frac{\omega \kappa^2}{4} \frac{R_1}{Q} D \quad (2)$$

$$R_1 = - \frac{\left[\frac{1}{\kappa} \frac{\partial E_x}{\partial r} \right]^2}{dp/dz} \quad (3)$$

$$Q = \frac{\omega W}{P_L} \quad (4)$$

$$\frac{R_1}{Q} D = \frac{D^2 A_0^2 \chi_0^2 / 4 J_1^2(\chi_0 a)}{\kappa^2 \omega W} \quad (5)$$

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where W is the stored energy within the cavity and $R_{\perp}$ is the transverse shunt impedance. P_L is the power loss on metal wall per cavity. D is the length of the cavity. $\kappa = 2\pi/\lambda$. $\omega = 2\pi f$, and f is the HEM_{11} mode frequency. χ_0 is the transverse wave number. A_0 is the field coefficient of the fundamental wave.

For test cavities (sixth cavity of SLAC C.G. section, $a = 1.29629$ cm; $b = 4.16878$ cm; $t = 0.5842$ cm; $f = 4139.6$ MHz; $\beta = 1.0$; $\Phi = 173.5^\circ$) the parameters computed by the variational method are as follows⁴ (see fig. 1):

$$Q_{11} = 14000; \quad \frac{R_{\perp}}{Q_{11}} = 18.7 \text{ } \Omega/\text{cm or } 65.4 \text{ } \Omega/\text{cell}$$

so from eq. (1) follows the formula below

$$U = 2 \times 10^{-13} r^2 (\mu) \left[\frac{N_{e-}}{5 \times 10^{10}} \right]^2 \text{ Joules} \quad (6)$$

and peak power

$$P_b = \frac{U}{dt} = 1.7 \times 10^{-3} r^2 (\mu) \left[\frac{N_{e-}}{5 \times 10^{10}} \right]^2 \text{ Watts} \quad (7)$$

where $dt = D/c = 0.117$ ns, the time for a bunch to pass through the cavity. N_{e-} is the number of electrons in a bunch.

In fact the bunch deposits energy into the whole pass-band of frequencies. The energy distribution deposited by the bunch versus frequency depends on the $R_{\perp}/Q$ and the phase velocity v_{11} at the corresponding frequency. The above estimate is approximate.

The Previously Tested Device

The device which has been tested is shown in fig. 2. The C -band waveguide (size 1.872 in $\times$ 0.872 in and cut-off frequency $f_c \approx 3152$ MHz) about half a meter long was used as a high-pass filter to selectively attenuate the 2856 MHz TM_{01} wave power ($I = 2.5$ db/cm at 2856 MHz) because H_θ and E_r field components are used to couple out power from both the HEM_{11} and TM_{01} mode. The TM_{01} power from the klystron is about 50 MW, which is more than ten orders of magnitude larger than that excited by the bunch.

The experiments show that the critical coupling ($\beta_c = 1$) is reached when the window size is about 0.8 in $\times$ 0.455 in (20 mm $\times$ 11.5 mm) in the cavity wall.

Experiments made with the device in the beam line (shown in figs. 3-6) indicate that the signal does not vanish (the signal output looks close to zero in fig. 4 because of smaller output signal; it can be seen that the signal is almost a factor of two smaller in fig. 4 than in fig. 3 when the beam displacement off axis is about 4 mm) when the beam is on axis and has a small constant value when the beam has a small displacement. It is not sensitive to small beam displacements off axis. There are several possible reasons to explain the experimental results. One is that the *C*-band waveguide is too short to obtain attenuation enough for the TM_{01} mode at 2856 MHz. The remedy is simply to increase the length of *C*-band waveguide. In this case there is no drive power from the klystron, so the attenuation of *C*-band waveguide should be enough to suppress the power of the TM_{01} mode just induced by the bunch itself. Another more substantial reason is that *C*-band waveguide is unable to attenuate the powers produced by higher-order symmetric modes, for example TM_{02} , TM_{03} and so forth (their frequency bands are all above $f_c = 3152$ MHz) induced by the bunch, which are almost independent of beam displacement off the axis and are much larger than that of the HEM_{11} mode when the beam displacement is small. They make a big background. A third possible reason is distortion of the beam bunch shape. The effect will be small if the bunch is small and is axially symmetric. The magnitude of the signal starts increasing outside the constant region when the beam is more off axis because the power of the HEM_{11} mode induced by the bunch is proportional to r^2 (r is the beam displacement off axis).

The Device Presented

A way to make the device more effective and even smaller is to detect a field component (for example H_r) that only exists in the HEM_{11} mode ($H_r = H_x = E_\theta = 0$ in the TM_{01} mode). The field amplitude distribution ($\cos \theta = 1$ or $\sin \theta = 1$) along the disk surface computed with variational method is shown in fig. 7. It can be seen that the field H_r on the surface of the disk at a point about 1.4 cm radially inward from the cavity wall reaches half the amplitude of H_θ on the cavity wall. The highest electric field occurs near the rounded part of the disk aperture along disk surface and then rapidly decreases with increasing r . The annular belt with $r = 2.6 \sim 3.0$ cm on the disk surface is a proper position for loops to be located. In this area the magnetic field is larger than electric field for the TM_{01} mode. Opening holes on the disk will lower the cavity frequency, but the decrease will be less than 0.5 MHz if the diameter of holes is not larger than 4 mm.

On the other hand, the presence of loops in that area leads to an increase in frequency. The proper size of loops, we think, is about 2×5 mm, which is a compromise between accuracy of beam position monitoring in the θ direction and field disturbance. A schematic design that uses two loops to couple the H_r field component on the disk surface is shown in fig. 8.

In order to decide the beam position in the X - Y plane, two loops placed orthogonally on the disk surface are needed. One detects the V -component and another the H -component. The power relations are

$$P_v = P_b \cos^2 \theta ; \quad P_h = P_b \sin^2 \theta \quad . \quad (8)$$

if the field is polarized in the H direction. We can determine r , the distance of the bunch off axis, and θ by detecting P_v and P_h .

The problem remaining to be solved is how to discriminate bunch position A from position B , which has the same r but 180° difference in θ (see fig. 8). A possible way to solve it is to detect the instantaneous wake field induced by the beam bunch while it is passing through the cavity.⁵ The wake fields induced by a bunch passing through the cavity in positions A and B are reversed in phase, so the currents induced in the loops are in opposite directions. In the previous device it is difficult to do this because the weak wake field signal of the HEM_{11} mode is swamped by TM_{01} wave signal from the klystron and by TM_{0n} signals from the beam itself, which are not only much larger in magnitude but also are almost independent of the beam position being A or B . By using loops the situation may be improved.

Another possible way is to offset the cavity with respect to the beam line (this is only good when using the BPM as an independent device in the colliding area of SLC) as shown in fig. 9. The offset is made a little larger than anticipated maximum beam displacement. This has the advantage of giving a large output signal even when the beam is very near the central beam line. A smaller size of loop in the θ direction can be used to improve the beam position sensitivity in the θ direction. First the beam position is determined in the cavity coordinates (x, y or ρ, θ) by formula (8), then they are transformed to beam line coordinates (x', y') by the following simple equations (see fig. 9)

$$x' = \rho \cos \theta - x_0 ; \quad y' = \rho \sin \theta - y_0 \quad . \quad (9)$$

The problem is that the accuracy will obviously decrease when beam has small displacement off axis.

The third way may be a combination of the two kinds of devices mentioned above, one coaxial and another off-axis with the beam line. The latter can be used for discriminating A from B position (fig. 8). It also provides an auxiliary method of monitoring beam position.

In fact, the presence of loops (or windows in the cavity wall) tends to rotate the HEM_{11} polarized mode towards symmetry with respect to the loops after the beam has passed through the cavity. This may add an error to the beam position measurement if the average field is detected during a time which is much larger than dt .

Computations show that the effects of higher-order modes, for example, EH_{12} (see fig. 10) EH_{21} and so on, are not important because their transverse shunt impedances are much less than that of the EH_{11} mode, and phase velocities are all larger than c (although certain space harmonics have phase velocity c , their effects still are not important).

Example of Numerical Computation

Suppose:

$$N_e = 5 \times 10^{10}; \quad r = 0.01 \text{ mm};$$

The energies induced by bunch per cavity are approximately:

$$U(HEM_{11}) \simeq 2 \times 10^{-11} \text{ Joules};$$

$$U(TM_{01}) \simeq 1 \times 10^{-4} \text{ Joules};$$

The practical way may be to detect the H_r field component with the loops on the disk surface and to transfer the signal by cable to a section of C -band waveguide in the instrument station. The waveguide would be used for attenuating possible power from the 2856 MHz TM_{01} mode from klystron and beam which couples due to errors in loop positions.

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Fig. 1

Fig. 2

VERT. HEM-BPM HØAG, SEEMAN 3/22/85

Fig. 3

HEM-BPM HØAG, SEEMAN 4/12/85

Fig. 4

HEM-BPM HØAG, SEEMAN 4/12/85

Fig. 5

HEM-BPM HØAG/SEEMAN 4/13/85

Fig. 6

Fig. 7

Fig 8

Offset Cavity to Beam Line

Fig. 9

Fig. 10

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