SCIENCE CHINA
Physics, Mechanics & Astronomy

• Research Paper •
Special Issue on the First Chinese Particle Accelerator Conference (2010)

December 2011 Vol.54 Suppl. 2: s292–s295
doi: 10.1007/s11433-011-4555-y

Design and cold test of S-BAND cavity BPM for HLS

LUO Qing*, SUN BaoGen, JIA QiKa, HE DuoHui & FANG Jia

National Synchrotron Radiation Laboratory, School of Nuclear Science and Technology, University of Science and Technology of China, Hefei 230029, China

Received April 29, 2011; accepted June 28, 2011; published online November 17, 2011

An S-band cavity BPM is designed for a new injector in National Synchrotron Radiation Laboratory. A re-entrant position cavity is tuned to the TM110 mode as position cavity. Cut-through waveguides are used as pickups to suppress the monopole signal. Theoretical resolution of this design is 31 nm. A prototype cavity BPM system is manufactured for off-line cold tests. The wire scanning method is used to calibrate the BPM and estimate the performance of the on-line BPM system. A cross-talk problem has been detected during the cold test. Racetrack cavity BPM design can be used to suppress the cross-talk. With the nonlinear effect being ignored, transform matrix can be used to correct cross-talk. Analysis of cold test results shows that the position resolution of prototype BPM is better than 3 μm.

cavity BPM, re-entrant, cut-through waveguide, cold test, wire scanning, resolution, cross-talk

PACS: 29.20.-c, 29.20.Ej, 29.25.Bx, 29.27.-a, 29.27.Fh

1 Introduction

The high brightness injector of Hefei Light Source (HLS) is designed for the development of new techniques of linac-based free electron laser (FEL), which could be the most probable scheme of the fourth generation light source. The fourth generation light sources require high quality electron [1] and also high precision control of the beam position. In recent years, cavity BPM is developed as a novel method that promises very high position resolution of beam [2]. Position resolution of the beam position monitor (BPM) for the 4–5 MeV photocathode RF gun of the new injector should be better than 10 μm. For a substantial improvement in the position resolution of BPM system, HLS decided to use cavity BPM, which promises much higher position resolution than the stripline BPM used at HLS before [3].

Pick-up station of a cavity BPM system is usually a cylindrical cavity mounted to beam-pipe. In general, the signal detected from the TM110 mode has a linear dependence on the absolute value of bunch displacement [4–7]. A reference cavity tuned to the TM010 mode is needed for reading the sign of bunch displacement. In our design, a re-entrant position cavity, instead of an ordinary pill-box cavity, is used to reduce the system size and the Q factor as well. The ideal position resolution could be 7 nm. With a noise factor of 10 from the electronics, the theoretical resolution is 31 nm.

The wire scanning method is often used to calibrate BPM systems. Prototype of the s-band cavity BPM is manufactured and a cold test is then performed. Results from the cold test of prototype are analyzed to estimate the performance of cavity BPM. The position resolution of cavity BPM system on-line can be better than 3 μm.

A Cross-talk problem caused by unpredictable distortions [8] is observed. Racetrack cavity BPM design is a way to suppress the cross-talk [9]. When nonlinear effect is negligible, the transform matrix can be used to distinguish position signal from cross-talk noise.

2 Re-entrant cavity BPM

A re-entrant cavity is used as position cavity in the pick-up

*Corresponding author (email: luoqing@mail.ustc.edu.cn)

station. Re-entrant cavity has much smaller size and much lower Q factor than a pill-box cavity with the same resonant frequency of TM110 mode. Size of the system can be controlled and a proper waveguide be chosen easily. Re-entrant cavity can still supply large position signal though abeam loses less energy in the re-entrant cavity.

Figure 1 shows parameters of the design. The thickness of metal walls is irrelevant with the performance of the BPM system so only the vacuum part of pick-up station is shown. Coaxial feed-through used in the design is the SMA type feed through NL-108-546, produced by Hitachi Haramachi Electronics Co., Ltd.

The position resolution is the minimum displacement for the electronics to get a signal voltage higher than thermal noise. If the electronics is ideal (noise factor $NF=1$ and all the energy loss in TM110 mode is coupled out to the electronics [10], there will be

$$\Delta x_{\text{ideal}} = \frac{1}{q}\sqrt{\frac{4kT(1+\beta)}{\pi\beta k_{\text{loss,nml}}}}, \quad (1)$$

where $k_{\text{loss, nml}}$ is the loss factor of TM110 mode normalized by bunch displacement and β is the coupling factor (the ratio between no load Q and external Q).

In a computer simulation, Q_0 is 3913.8, Q_e is 298.1 and $k_{\text{loss, normalized}}=1.14\times10^{14}\ \Omega\ \text{m}^{-2}\ \text{s}^{-1}$. The electronics get about 52% of the total energy loss in TM110 mode. Assume that NF of electronics is 10 and then the theoretical resolution can be gotten from eq. (1):

$$\Delta x_{\text{theoretical}} = \frac{1}{q}\sqrt{\frac{4kT(1+\beta)}{\pi\beta k_{\text{loss,110,nml}}}}\sqrt{\frac{NF}{0.52}}. \quad (2)$$

When the bunch charge is 1 nC, the ideal resolution is 7 nm and the theoretical resolution is 31 nm. The external Q of monopole mode obtained from the simulation is 2.6×10^{13}, so the monopole mode is successfully suppressed.

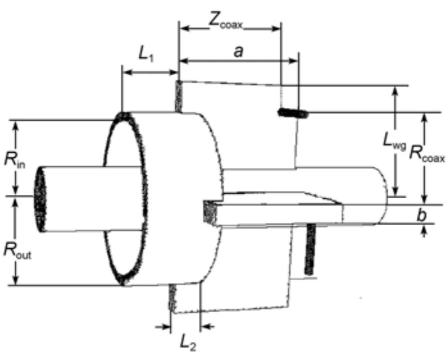

Figure 1 Structure of the vacuum part of BPM. The parameters (in mm) are: R_{in}, 44.000; R_{out}, 47.900; L_1, 30.304; L_2, 10.000; a, 70.000; b, 10.000; L_{wg}, 65.000; Z_{coax}, 55.060; and R_{coax}, 55.050.

3 Cold test and analysis

A prototype cavity made of duralumin is manufactured for cold tests. Here duralumin is used because it works easily and is cheap and light.

Two cold test methods are used to study the prototype cavity and estimate the performance of the on-line BPM system. A network analyzer is used to get the transmission characteristic of prototype cavity. For an estimation of the position resolution, displaced analogue signal at the resonant frequency of TM_{110} mode is input to the prototype cavity to simulate displaced beam and oscilloscope is used to get the amplitude of response signal coupled out from the probes. Figure 2 shows the definitions of ports used in the cold test and Figure 3 shows a sketch of wire scanning calibration platform.

Figure 4 shows the transmission characteristic curve from port 3 to port 4. Two peaks of dipole modes under −25 dB can be found, so there is x-y coupling about 5%–10%, which means there are distortions.

The curves shown in Figures 5 and 6 describe how the signal amplitude responds to displacement of the metal wire. The oscilloscope is set to the average mode so as to reduce the error. The amplitude of excitation signal is 1.5 V while the frequency is the same as the resonant frequency of TM_{110} mode.

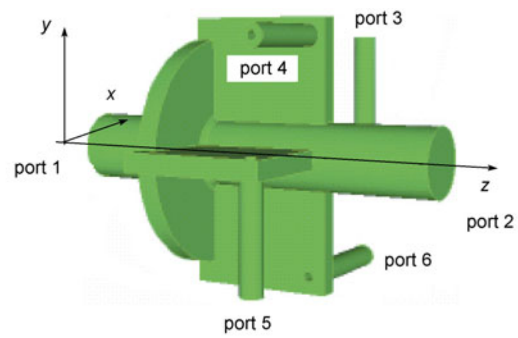

Figure 2 (Color online) Definition of ports used in the cold test.

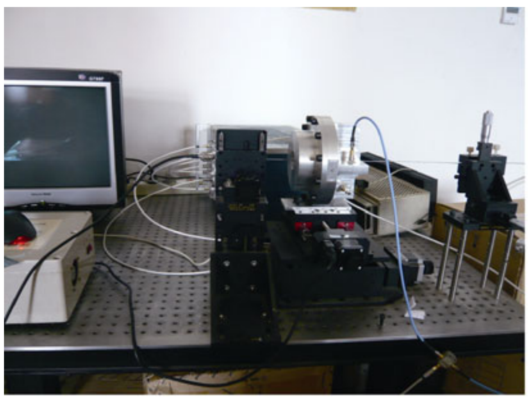

Figure 3 (Color online) Sketch of the calibration platform.

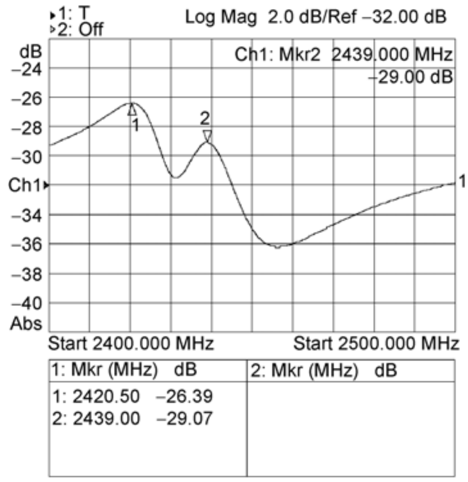

Figure 4 The *x*-*y* transmission curve.

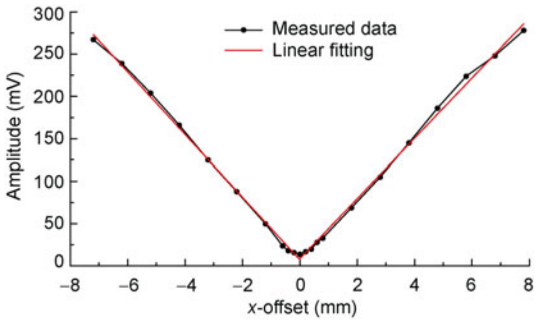

Figure 5 (Color online) Amplitude vs. *x* displacement.

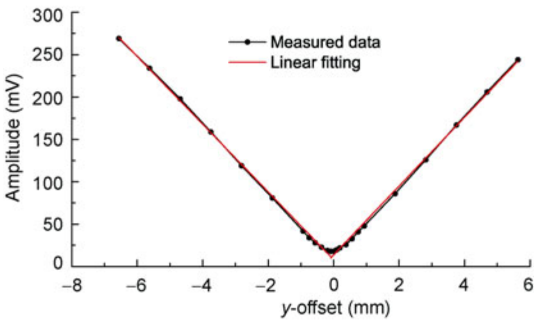

Figure 6 (Color online) Amplitude vs. *y* displacement.

The least square method was used in analyzing the results of experiments. Amplitude sensitivity in the *x* direction is 40.1 mV/mm, while in the *y* direction it is 41.5 mV/mm.

The off-line test resolutions in different directions are shown below:

$$\begin{cases} \langle d \rangle_x = 0.018 \text{ mm}, \\ \langle d \rangle_y = 0.019 \text{ mm}. \end{cases} \tag{3}$$

Amplitude sensitivity on-line can be treated in the same way as the theoretical value [11]:

$$\begin{cases} \eta = \dfrac{2}{\pi} \operatorname{arctg}\left(\dfrac{\Delta F Q_{L,110}}{f_{110}}\right) \dfrac{Q_{0,110} - Q_{L,110}}{Q_{0,110}}, \\ V_{110}^{\text{out}} = qr\sqrt{Z_0 \eta \dfrac{k_{\text{loss},110,\text{nml}}}{2} \dfrac{\omega_{110}}{Q_{e,110}}}. \end{cases} \tag{4}$$

Sensitivity on-line is 382.9 mV/mm in the *x* direction and 381.9 mV/mm in the *y* direction, larger than it is off-line, generally because the excitation is much stronger. The real resolution can be estimated as below:

$$\begin{cases} \delta_x = 0.018 \times 40.1 / 382.9 \text{ mm} = 1.9 \ \mu\text{m}, \\ \delta_y = 0.019 \times 41.5 / 381.9 \text{ mm} = 2.1 \ \mu\text{m}. \end{cases}$$

In fact the real resolution may be better because the precision of oscilloscope is not very high. The maximal measurement error is 1 mV. In order to get results with greater precision, an s-band RF signal receiver is needed.

4 Cross-talk correction

The cross-talk is mostly contributed by the linear coupling between pick-ups. This type of coupling can be described by a matrix $M_{\text{coupling}} = \begin{pmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{pmatrix}$. Because of conservation of energy, the matrix satisfies:

$$\begin{cases} C_{11}^2 + C_{21}^2 = 1, \\ C_{12}^2 + C_{22}^2 = 1. \end{cases} \tag{5}$$

In this case the coupling matrix can be solved from a system of binary equations formed by the measurement results. So the cross-talk problem can be corrected under the assumption that there is no non-linear coupling.

Mechanic errors and distortions result in cross-talk problems. If an asymmetrical structure such as a racetrack cavity BPM is used, linear coupling from distortions can be suppressed [9]. Figure 7 shows a racetrack cavity.

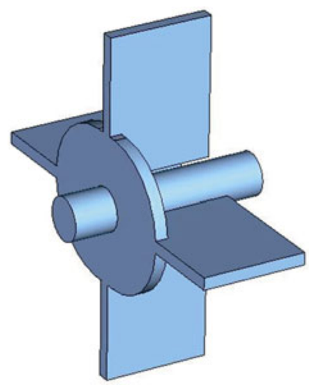

Figure 7 (Color online) Sketch of the racetrack cavity BPM.

5 Conclusions

Re-entrant cavity BPM is a good solution for high precision control of beam position and it can reach a high resolution better than 3 μm. With high precision RF signal processing system the performance of cavity BPM system can be still improved. Cross-talk from distortions could be a problem to cavity BPMs. Transform matrix is a way to correct cross-talk when the nonlinear effect is negligible.

Special thanks go to Dr LI Zenghai and Advanced Computations Department of SLAC, who gave the authors a lot of kind help. This work was supported by the National Natural Science Foundation of China (Grant Nos. 10875117 and 11005106), National "985 Project" (Grnat No. 173123200402002), China Postdoctoral Science Foundation (Grant No. 20100470853) and "the Fundamental Research Funds for the Central Universities"

1 Winick H. The linac coherent light source (LCLS): A fourth-generation light source using the SLAC linac. J Electron Spectroscopy Related Phenomena, 1995, 75: 1–8
2 Sargsyan V. Tesla Reports 2004-03, 2004
3 Li J H, Sun B G, He D H, et al. Research and measurement of BPM system at HLS LINAC. HEP & NP (in Chinese), 2007, 31(01): 96–100
4 Lorenz R. Cavity beam position monitors. In: Proceedings of 1998 Beam Instrumentation Workshop. SLAC, Stanford, 1998. 53–73
5 Maesaka H, Otake Y, Togowa K, et al. Beam position monitor at the SCSS prototype accelerator. In: Proceedings of APAC 2007, Indore, 2007. 387–389
6 Walston S, Boogert S, Chung C, et al. Performance of a high resolution cavity beam position monitor system. Nucl Instrum Methods Phys Res A, 2007, 578: 1–22
7 Lunin A, Romanov G, Solyak N, et al. Design of a submicron resolution cavity BPM for the ILC main linac. In: Proceedings of the DIPAC'07, Venice, 2007. 192–194
8 Sargsyan V. Cavity Beam Position Monitor for the TESLA-cryomodule. Cross-Talk minimization. Dissertation for the Doctoral Degree. Berlin: Technische Universität Berlin, 2003
9 Luo Q, Sun B G, He D H, et al. Beam position monitor with racetrack cavity. High Power Laser Particle Beams, 2010, 22(07): 1635–1639
10 Li Z. S-band cavity BPM for ILC. In: Proceedings of 2005 ILC Physics and Detector Workshop and 2nd ILC Accelerator Work-shop (Snowmass 2005), 2005. http://www.hep.ucl.ac.uk/ lc/T474/Documentation/ILCAW0901_TALK.PDF
11 Luo Q, Sun B G, He D H. Design of s-band re-entrant cavity BPM. Nucl Sci Tech, 2009, 20(03): 133–139