# RF measurements of a C-band cavity beam position monitor*

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**Abstract** RF cold test of a novel C-band cavity beam position monitor (PBM) to be used in the SDUV-FEL Test Facility is described. The test results are presented and some characteristics discussed. The main parameters obtained are in reasonable agreement with the analytical estimations. Effective suppression of the common mode has been demonstrated. The position sensitivity over the test region of ±0.5 mm is about −21.58 dB/10 μm for the $TM_{110}$ mode and is linear in the central region of the BPM cavity.

**Key words** cavity BPM, $TM_{110}$ mode, $S$-parameter, position sensitivity

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## 1 Introduction

The SDUV-FEL Test Facility is designed for a coherent radiation in the spectral region from 264 to 88 nm[1]. It is necessary to have a very precise beam position control to ensure the overlap between the electron beam and the generated photon beam over the entire length of the undulators. Beam dynamics simulations indicate that the mean variation between photon path and electron trajectory must be kept under a level of several μm to reach saturation in the undulators. This requirement can only be fulfilled with a beam based alignment procedure based on dispersion[2], which requires the transverse beam position to be measured at several points inside and between the undulator modules with a resolution better than 10 μm. Among various types of BPMs, such as button-pickups or stripline-type BPM, only the cavity BPM has the potential to achieve a resolution in the submicron range and the center accuracy at the μm level[3]. To meet these demands, we have designed a novel C-band Cavity BPM. This paper presents the RF cold measurements of the prototype on a testbench.

## 2 Details of Cavity BPM

The proposed cavity BPM is based on a dipole mode $TM_{110}$ resonant cavity. The horizontal and vertical positions of an off-center beam are given by the excitation of the two polarizations of the $TM_{110}$ mode, the amplitude of which scales with the beam displacement and the bunch charge, and its phase relative to an external reference gives the sign of the displacement.

For cylindrical cavity BPM, the voltage of the $TM_{110}$ excited by electron beam at the displacement $\Delta x$ can be estimated as[4]

$$V_{110}^{\mathrm{in}}=\left(\frac{R}{Q}\right)_{110}\omega q\frac{\mu_{11}\Delta x}{2J_1^{\max}R}\ , \tag{1}$$

where $q$ is the beam charge, $\mu_{11}$ the first root of Bessel function $J_1$, $\omega$ the dipole mode angular frequency, $R$ the cavity radius, and $\left(\frac{R}{Q}\right)_{110}$ the normalized shunt impedance of $TM_{110}$ mode. For a given coupling coefficient $\beta$, the output signal voltage on a 50 Ω coupling probe can be calculated as

$$V_{\mathrm{out}}=V_{110}^{\mathrm{in}}\left(\frac{R}{Q}\right)_{110}^{-\frac{1}{2}}\sqrt{\frac{50\beta}{Q_0}}\ . \tag{2}$$

Since the field maximum of the common mode

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$TM_{010}$ is on the cavity axis, it will be excited much stronger than the dipole mode by a beam. The voltage of the $TM_{010}$ with respect to the $TM_{110}$ at frequency $\omega_{110}$ can be estimated as[5]

$$S_1 = \frac{V_{010}(\omega_{010})}{V_{110}(\omega_{110})} \approx \frac{1}{\Delta x}\frac{\lambda_{110}}{5.4}\frac{k_{110}}{k_{010}} \ , \tag{3}$$

where $\lambda_{110}$ is the wavelength of $TM_{110}$ mode, $k_{110}$ and $k_{010}$ are the loss factors of $TM_{110}$ and $TM_{010}$ modes, the common mode voltage excited in the cavity is about 80 dB higher as the voltage of the dipole mode. For the common mode rejection, we use a novel coupling scheme, as shown in Fig. 1. The two polarizations of the dipole modes are coupled magnetically to four waveguides spaced by 90° around the circumference of the cavity, the waveguide mode does not have azimuthal magnetic fields in the coupling, and hence there is no coupling to the cavity $TM_{010}$ mode[6].

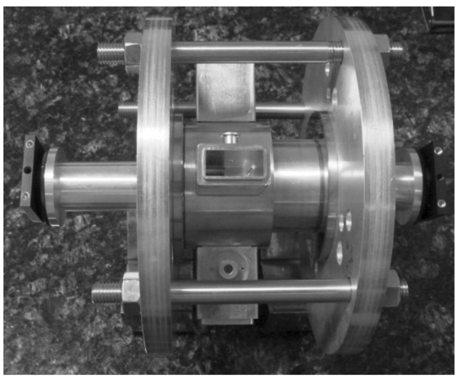

Fig. 1. Photograph of the cavity BPM.

The dimensions of this C-band BPM cavity are 60.8 mm in diameter and 20 mm in length, with $TM_{110}$ dipole mode designed as 5.712 GHz. In addition to the BPM cavity there is a reference cavity where the monopole mode resonates at 5.712 GHz. The reference cavity dimensions are 43 mm in diameter and 15 mm in length. The voltage of the common mode $TM_{010}$ in reference cavity excited by a beam is proportional to the beam current, so we can use $TM_{010}$ mode for beam current measurement.

## 3 RF cold test

RF cold test was made with a measurement setup consisting of a vector Network Analyzer, multi-way microwave switches and a precision moving stage. Fig. 2 shows the test arrangement for the cavity BPM prototype and the definition of the ports number. The electron beam was simulated by placing an antenna near the axis of the BPM cavity, which was excited by the RF signal fed by the Network Analyzer. The antenna was mounted on a moving stage, which was stepped in 10 μm increments (vertical or horizontal direction) over a range of ±3 mm. 50 Ω vacuum feedthroughes were inserted into the waveguides for the $TM_{110}$ signal coupling. Both the excitation antennas in the beam pipe and coupling feedthroughes in the waveguides were connected to the Network Analyzer for scattering parameters measurements.

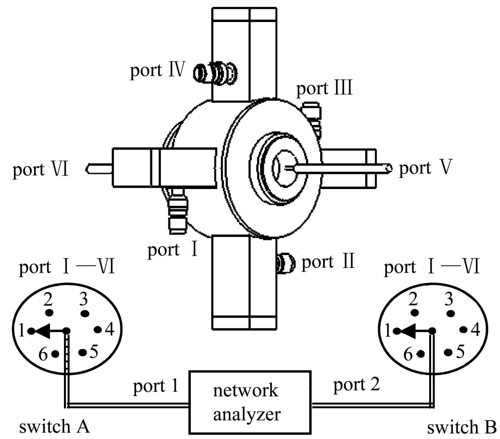


Fig. 2. Test arrangement for the BPM.

The transmission measurement on the two opposite antennas along the beam pipe was made to observe the first two modes of the BPM cavity. As shown in Fig. 3, two resonant peaks at 3.8 GHz and 5.72 GHz in the spectrum are clearly visible, they are the $TM_{010}$ common and $TM_{110}$ dipole modes, other peaks are higher order modes which can propagate out of the cavity through the beam pipe, these modes can easily be rejected by a band pass filter.

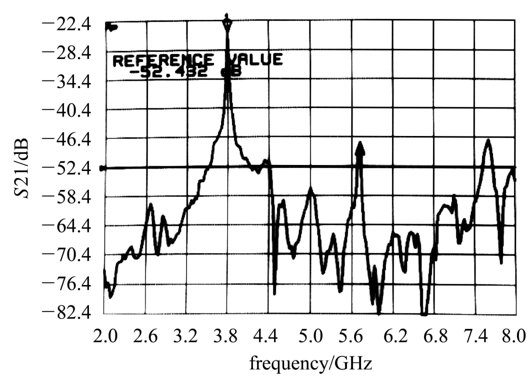


Fig. 3. Frequency response of the BPM cavity.

The transmission measurement on the waveguide ports and the antenna placed in the beam pipe was carried out to check the suppression of the $TM_{010}$ mode. As seen in Fig. 4, the 3.8 GHz peak has disappeared from the spectrum, the suppression of the $TM_{010}$ mode is about 50 dB.

The loaded $Q$ value of $TM_{010}$ mode is 8951. For the $Q$ value measurement of $TM_{110}$, it has two cases. While the four waveguide ports are connected with 50 Ω matched load, the loaded $Q$ value is 3682, and the loaded $Q$ value is 10377 with all ports connecting with short load. The value is very close to the calculated unloaded $Q$ value 11035. So we can use the measured $Q$ value to estimate the coupling coefficient of the $TM_{110}$ mode, which is about 1.0, as enough for the front-end signal processing system.

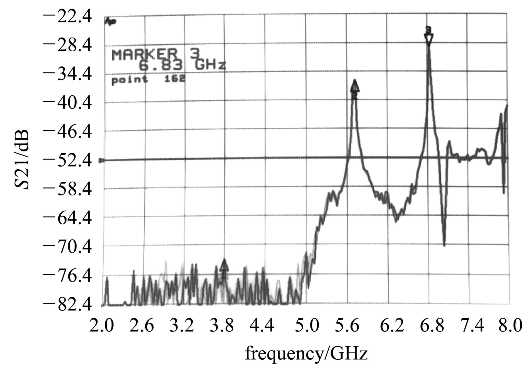


Fig. 4. Transmission response between ports Ⅳ and Ⅴ.

For the position sensitivity measurement, we can measure the magnitude of transmission paramater S21 between the waveguide ports and the antenna placed in the beam pipe. While moving antenna in the vertical direction, waveguides Ⅰ and Ⅲ in the horizontal direction will be excited, the other two waveguides Ⅱ and Ⅳ in the vertical direction will not respond to it. Conversely, while moving antenna in the horizontal direction, the response pattern will be reversed.

For a single scan, the dipole mode magnitude of S21 between the waveguide ports in the vertical direction and the antenna vs. the horizontal offset are shown in Fig. 5. It shows that Port Ⅱ and Port Ⅳ have a large response to the offset of the antenna and the cavity response is linear in the central region (±1 mm) of the BPM cavity. The position sensitivity over a region of ±3 mm is about 9.25 dB/mm.

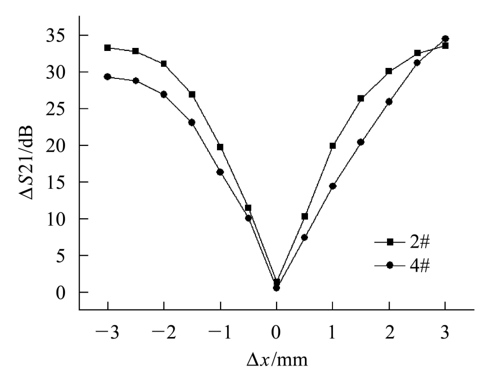


Fig. 5. Relative magnitude of S21 vs. the horizontal offset.

We can also use perturbation method to measure the position sensitivity. A thin metal wire was placed along the axis of the beam pipe, both ends of the wire were connected to the moving stages with 20 μm increments in the horizontal direction, the field loss into the metal wire is propotional to the integral of the $R/Q$ along the wire. With careful experimental setup, the wire was moved in the horizontal direction while the magnitude of S21 between the opposite waveguide ports in the vertical direction were monitored by the network analyzer. The decrease of the S21 magnitude is propotional to the integral of the $R/Q$ along the wire. Magnitude of S21 in linear scale vs. the horizontal offset is shown in Fig. 6. The position sensitivity over a region of ±0.5 mm is about −21.58 dB/10 μm.

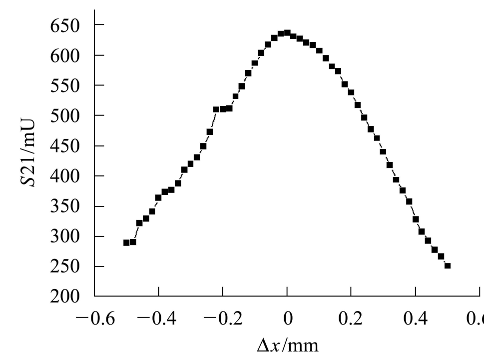


Fig. 6. Magnitude of S21 vs. horizontal offset of the metal wire in the beam pipe.

The cross-talk isolation is another important parameter, which shows how good the signals corresponding to the horizontal and vertical beam offsets are isolated from each other. For the cross-talk isolation measurements, we tested the transmission parameters on the opposite waveguide ports at the same direction while the two remaining waveguide ports were loaded by 50 Ω, and then tested the transmission parameters on the neighbor waveguide ports. The tested S21 value for opposite waveguide ports Ⅰ and Ⅲ is −4.2 dB, and S21 value for neighbor waveguide ports Ⅰ and Ⅱ is −34.5 dB, as shown in Fig. 7. So the cross-talk isolation value is 30.3 dB for the ports Ⅰ and Ⅱ. The cross-talk isolation value is at the same level (better than 29 dB) for other ports.

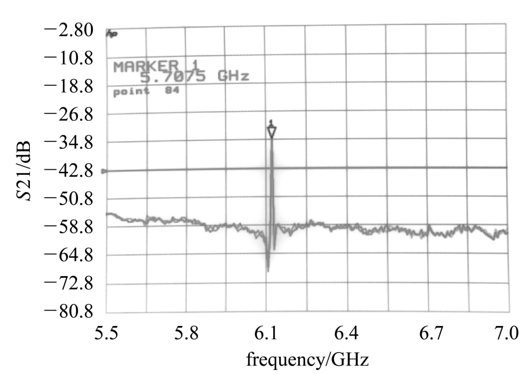


Fig. 7. The cross-talk isolation between neighbor waveguides.

## 4 Conclusion

A prototype BPM cavity was constructed and tested. The main test results confirmed the functionality of the cavity BPM and the capability to measure the beam offsets with high resolution in the test region over ±0.5 mm off the center of the beam pipe. A high degree of common mode rejection was obtained by the waveguide coupling scheme. The main parameters of the cavity dipole mode agree well with the theoretical expectations.

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