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Development of button-type pickup for SSRF ring (Postprint)

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Abstract

In building Shanghai Synchrotron Radiation Facility (SSRF), in order to reduce or eliminate the unnecessary sources of beam motion, the precise and stable beam position measurement system in the feedback system was required. In this study, we focused on theoretical analysis of the electrode of beam position monitor (BPM). Simulations, including analytic derivations of the propagation impedance and the distribution inductance, were performed. The BPM was designed based on the results and the acceptance measurements of the impedance and the inductance by using the time domain reflection (TDR) with a network analyzer. It has been proved in years of operations that the BPM system meets the requirement of the resolution of sub-micron.

Full Text

Preamble

Development of Button-Type Pickup for SSRF Ring

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In building the Shanghai Synchrotron Radiation Facility (SSRF), a precise and stable beam position measurement system was required for the feedback system to reduce or eliminate unnecessary sources of beam motion. This study focuses on theoretical analysis of the beam position monitor (BPM) electrode. Simulations, including analytic derivations of the propagation impedance and distribution inductance, were performed. The BPM was designed based on these

results, and the impedance and inductance were verified through acceptance measurements using time domain reflection (TDR) with a network analyzer. Years of operation have proven that the BPM system meets the requirement of sub-micron resolution.

Keywords: SSRF, BPM, Position sensitivity, Cut-off frequency, Distributed capacitance

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Introduction

The Shanghai Synchrotron Radiation Facility (SSRF) has a storage ring with a circumference of 432 m, operating at 3.5 GeV [1]. During commissioning and routine operation, the button-type BPMs play a key role in ensuring stable high-performance operation. They provide position information to the orbit feedback system, transverse feedback system, safety interlock system, and others, at required precisions and rates. Specifically, the high-precision closed orbit position feedback system tracks position with 1 μm resolution at 2 Hz bandwidth, the transverse feedback system requires bunch-by-bunch position signals with 10 μm resolution at 250 MHz bandwidth, and turn-by-turn measurements need resolution and data rates between these two extremes. For the BPM detector itself, the main technical challenge is ensuring high signal-to-noise ratio (SNR) for bunch-by-bunch signals while avoiding beam impedance mismatch and higher-order mode (HOM) excitation. This paper discusses detailed technical issues involved in BPM design according to SSRF beam parameters.

II. Design Objectives

In different SSRF commissioning and routine operation scenarios, the button-type BPM must provide position information at varying precisions and rates. Table 1 shows the major beam parameters of the SSRF accelerator. BPM requirements differ slightly across accelerator operation stages: during preliminary commissioning, higher beam charge sensitivity (larger button size) and higher position sensitivity are needed due to small beam charge and large orbit distortion; during user operation, lower beam charge sensitivity (smaller button size) and lower position sensitivity are required due to high average beam current and high position resolution demands. To meet these requirements and work with the beam parameters in Table 1 while providing appropriate signals to the electronics system, the button-type BPM should achieve the specifications listed in Table 2 .

To meet these goals, BPMs must have appropriate sensitivity, size, and internal structure—large enough to provide strong signals but as small as possible to avoid HOMs, with appropriate electrode separation to achieve desired sensitivity and an internal structure that transmits signals effectively. BPM simulations were performed using the MAFIA code to optimize a structure balancing transfer and coupling impedances.

III. Physical Designs

The BEPCII BPM simulation [5] provides a valuable reference for modeling SSRF BPMs with the MAFIA code (Fig. 1 [Figure 1: see original paper]). A BPM electrode is mounted on the inner surface of the beam pipe. The beam pipe geometry determines the BPM geometry except for the electrode size and location. The SSRF storage ring beam pipe has an octagonal cross-section, with four button electrodes symmetrically arranged on the upper and lower planes.

BPM position sensitivity should be as high as possible, with sensitivities in the horizontal and vertical planes as close as possible. Sensitivity is determined by signals picked up by different electrodes when the beam is off-center. We adopt the sensitivity function [6]:

$$S_i = \frac{A - B}{(A + B)d_i}$$

where S_i and d_i are the offset in the x or y direction (subscript i denotes either x or y), and A and B are signals picked up by the right top and right bottom monitors, respectively.

For SSRF BPMs, the optimized electrode diameter is 10 mm. The infinite element simulation results are given in Table 3. G is the distance between the axes of two electrodes on the same horizontal plane; K_x and K_y are position sensitivities in horizontal and vertical planes, respectively; ρ is the normalized line density of induced charge at the electrode center, determined by the vacuum chamber structure and electrode size and position; $g = \rho^2\pi B$ is the shape factor (B is the distance between the electrode center and geometric center of the vacuum chamber), representing deviation from the induced charge distribution at the electrode center relative to a circular chamber. As shown, adjusting the relative electrode position aligns BPM sensitivities in horizontal and vertical directions.

Beam position measurement can be influenced by electrode output signal intensity. The signal must be large enough to meet input power requirements of signal processing electronics but not so strong as to break vacuum sealing at high currents. We finally chose $G = 16$ mm. The button pickup must work properly in single-bunch mode with low current (0.02 mA) and multi-bunch mode with high current (300 mA). The signal processing electronics require input signal power greater than -85 dBm and smaller than 5 dBm across a 9 MHz bandwidth. Combined with insertion loss (around 5 dB) of signal cables, this translates to pickup output requirements of greater than -80 dBm and smaller than 0 dBm. Fig. 2 [Figure 2: see original paper] shows the output voltage and frequency spectrum of a 10 mm diameter electrode with 1 nC single-bunch charge.

The output power (P) at working frequency for the signal processing electronics is:

$$P = \frac{U^2(\omega_0) \cdot \Delta\omega}{R \cdot \Delta t}$$

where U is the output voltage of the corresponding spectrum (varying with ω_0 , the center frequency of signal processing electronics), $\Delta\omega$ is the work bandwidth, R is 50Ω , and Δt is the revolution time. With a $\$10$ mm button BPM, the spectral intensity for signal processing electronics is 5.5×10^{-10} V/Hz at center frequency during SSRF single-bunch operation. The electrode output signal power at different beam currents (Fig. 3 [Figure 3: see original paper]) fully satisfies SSRF operation under various conditions.

HOMs present significant challenges [7, 8]. The TE₁₀ mode of the beam pipe may cause errors in beam position measurement. Pipe length and height must be considered (height = 10 mm, length < 175 mm). The TE₁₀ mode within the cut-off frequency (< 499.654 MHz) reduces BPM resolution, and higher slots cause more transverse impedance. Calculations show the cut-off frequencies of higher-order modes within the pipe structure are 2.449, 4.412, 4.732, 4.800, 5.464, 6.322, 6.729, 7.220, 8.201, and 8.259 GHz—much larger than the signal processing center frequency (499.654 MHz). Therefore, TE modes that could couple into the signal processing circuit through the BPM electrode cannot be excited, meaning TE modes will not affect the position measurement system.

Simulations also examined longitudinal wakefield influence, with results shown in Fig. 4 [Figure 4: see original paper]. By integrating wakefield energy loss, the BPM structure energy loss factor is $k = 0.0166$ V/pC. Generally, the energy loss factor is particularly sensitive to electrode size and the gap between electrode and vacuum tube wall. To prevent large beam power loss while considering BPM machining constraints, a 0.3-mm gap was chosen.

IV. Technical Designs

For technical design and tolerance analysis, we primarily consider impedance matching of the ceramic sealing section and electrode capacitance. Induced BPM signals transfer through a vacuum-seal ceramic section whose structure must match the characteristic impedance of the signal transmission path to avoid complex higher-order mode and coupling problems [7, 8]. Two approaches can achieve impedance matching: gradual transition of both inner and outer conductor structures, or shielded dielectric transition. Drawing on experience from other accelerator laboratories, we adopted the shielded medium transition ceramic sealing structure (Fig. 5 [Figure 5: see original paper]). The ceramic welding in the vertical direction is divided into two sections—the ceramic section welded with the outer conductor has some freedom in the inner conductor direction, and vice versa—avoiding ceramic structure damage from welding or normal operational thermal expansion.

To avoid reflection of incident electromagnetic fields at different transmission structures, characteristic impedance matching must be considered. For SSRF

ceramic structures, when characteristic length is comparable to or smaller than the transmitted electromagnetic wavelength, characteristic impedance can be analyzed using TEM mode field structure. For the upper ceramic structure, its characteristic impedance, capacitance, and other parameters can be obtained through equivalent dielectric constant. For the TEM model, assuming unit length of inner conductor with free charge q , Maxwell's equations give the surrounding electric field:

$$E(r) = \frac{q}{2\pi\epsilon r}$$

where r is radial distance from the inner conductor center and ϵ is the dielectric constant at that point. After electric field integration, the voltage difference between inner and outer conductors is:

$$V = \frac{q}{2\pi\epsilon_1} \ln \frac{c}{a} + \frac{q}{2\pi\epsilon_2} \ln \frac{b}{c}$$

where a is the center conductor radius, b is the inner radius of outer conductor, and c is the ceramic medium radius.

We therefore consider the mixed medium as a single medium with equivalent dielectric constant:

$$\epsilon_{eq} = \frac{\epsilon_1\epsilon_2 \ln(b/a)}{\epsilon_2 \ln(c/a) + \epsilon_1 \ln(b/c)}$$

The characteristic impedance and distributed capacitance of the structure are then given by:

$$Z_0 = \frac{1}{2\pi} \sqrt{\frac{\mu}{\epsilon_{eq}}} \ln \frac{b}{a}, \quad C = \frac{2\pi\epsilon_{eq}}{\ln(b/a)}$$

Figure 6 [Figure 6: see original paper] shows TDR test results for the upper ceramic structure before and after optimizing the inner conductor outer diameter (0.92 mm and 1.5 mm). The equivalent dielectric constant was used in optimization, and the optimized BPM characteristic impedance achieves smoother transition.

BPM wakefield impedance is inversely proportional to its ground capacitance, which is primarily determined by electrode ground capacitance. The distributed capacitance of the ceramic dielectric section also significantly contributes to ground capacitance. For coaxial structures, ground capacitance can be calculated by:

$$C = \frac{2\pi\epsilon \cdot H}{\ln(1 + \text{gap}/r)}$$

where ε is the dielectric constant, H is structure length, and gap is the distance between internal and external conductors. For the BPM, electrode distributed capacitance is 954 pF/m, upper ceramic structure equivalent dielectric constant is 5.3 (corresponding characteristic impedance 50.2 Ω , coaxial capacitance 150 pF/m), lower ceramic structure equivalent dielectric constant is 2.55 (corresponding characteristic impedance 66 Ω , coaxial capacitance 80 pF/m), and total capacitance is about 2.4 pF.

Electrode structure distributed capacitance can be determined from TDR test rise time—244 ps (10–90%) when BPM electrode terminal is open, corresponding to electrode capacitance of 2.2 pF for 50 Ω input impedance, consistent with theoretical expectations.

Manufacturing errors are inevitable. To guarantee button capacitance, tolerance of the gap between round disc and beam pipe is (300 ± 25) μm , button positioning error is 0.1 mm, and manufacturer reading errors are 0.025 mm and 0.1 mm in X and Y directions, respectively. These errors can be corrected through mapping tests or beam-based alignment (BBA).

V. Factory Acceptance Test

The completed assembly unit is shown in Fig. 7 [Figure 7: see original paper]. Test inspections were performed to confirm product quality meets requirements, with results shown in Table 4. As an example, Fig. 8 [Figure 8: see original paper] shows step response inspection results for 10 randomly sampled units using TDR scope. The BPM performs excellently and consistently, proving products fully meet design goals.

Spatial resolutions for narrow-band (10 Hz data rate, 2 Hz bandwidth) and broad-band (694 kHz data rate, 347 kHz bandwidth) BPM data were evaluated during user operation. Results show sub-micron resolution for slow data (Figs. 10(a) and 10(b)) and micron-level resolution for fast data (Fig. 10(c)) have been achieved.

VI. Practical Application

A total of 140 BPM sets have been implemented in the SSRF storage ring since onsite inspection in 2007. Various operation modes have been performed over the past six years, including single-bunch with low charge (0.03 nC), 500 bunches with high current (300 mA), and different hybrid filling modes. The BPM system has proven highly successful. Fig. 9 [Figure 9: see original paper] shows a button signal measured with low-current single-bunch in the storage ring, which perfectly matches theoretical expectation.

VII. Conclusion

By simulating electrode structures and BPM layouts, button-type BPM sensitivity was optimized. TE₁₀ mode studies helped suppress HOMs that could

occur in the vacuum chamber. Acceptance tests confirmed simulated electronic characteristics. SSRF operations have proven the BPM system meets primary requirements with long-term availability, even during hybrid filling modes that often cause heat load problems.

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