DEVELOPMENT OF NANOMETER RESOLUTION RF-BPMs

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Abstract:

The future e+e- linear colliders will use high resolution and high accuracy BPMs. A highest resolution of 10 nm is required for the beam-based alignment of magnetic elements in the final focus system. Very tight zero-point center accuracy, in the range of 1 to 10 μm, is required to align the accelerating structures in the main linac. The cavity type RF-BPM (Radio Frequency Beam Position Monitor) is one of the best candidates to meet those demands.

This paper describes a brief history of high resolution RF-BPM development, the beam test of C-band BPM at FFTB beam line, analytical models of resolution and accuracy in a simple pillbox-cavity BPM.

1. Introduction

Future linear colliders [1] will require high performance BPMs to control the beam trajectory with high precision in order to maintain a stable collision of nanometer size beams at the interaction point. The BPM has to be high sensitive (= high resolution) and highly accurate (= high zero-point center accuracy).

In the main linacs, it is essential to minimize the transverse wakefield effect in the accelerating structure, hence the structure has to be accurately aligned to the beam. The typical estimated tolerances are in the range of 1 *μm* in 30 GHz CLIC design, a few *μm* in X-band NLC, and 10 *μm* in C-band JLC. The cavity RF-BPM directly attached to the accelerating structure will be a possible candidate to perform this alignment.

On the other hand, in the final focus system, the high resolution BPM is required. In order to maintain the beam spot in a few nm vertical size at IP, the magnetic center of the focusing elements (quadrupole and sextupole magnets) have to be aligned to the beam with tight tolerance. For example in the JLC design, the tightest tolerance is around 150 nm for 10% increase of the vertical spot size [2]. To find the magnetic center, the beam-based-alignment technique will be used [3], where a very high position resolution around 10 nm is required.

Among various type of BPMs, such as the electrostatic BPM using four button-pickups or the stripline type BPM, only the cavity RF-BPM has a potentiality to achieve the resolution of nm range and the center accuracy of μm level.

According to the accelerating structure alignment, there is another scheme, which is under development at NLC project. The wakefield power induced in the accelerating structure will provide direct information of the cavity displacement from the beam. The TM110 mode in the accelerating structure can be to detect the beam position. This idea is so called the structure BPM, which is planed to be used in the NLC design and its powerfulness was demonstrated with beam in ASSET test [4]. Since the basic mechanism in this scheme is exactly same as that in the cavity RF-BPM, we will focus our discussions into the cavity RF-BPM in this paper.

2. Brief History of Cavity RF-BPM

The basic idea of the cavity RF-BPM is quite old, which backs to 1960's. When SLAC was built, this type of BPMs were installed in the drift-section along the two-mile accelerator, and in the beam switchyard [5]. The TM120 mode resonates 2856 MHz in a rectangular cavity was used to detect x or y position according to cavity orientation. A cylindrical cavity of TM010 mode is used to measure the beam current intensity and provides the phase reference. The typical sensitivity was 0.5 mm for beam pulse current in the range of 1 to 300 mA.

From that time, various configurations of BPM cavities and detection circuits have been developed in many laboratories and widely used to monitor the beam trajectory mostly in the linear accelerators [6, 7, 8].

When R&D projects for the future e+e- linear colliders started in 1980's, problems to develop high resolution and high accuracy BPMs were discussed in many literatures. G.E. Fisher discussed a possibility of high-resolution BPMs for TeV linear colliders [9], and concluded "resolutions in the micron range are not impossible making use of modern microwave technology in the centimeter, perhaps millimeter wavelength range". W. Schnell discussed the common-mode problem associated with the cavity RF-BPM [10], which restricts the position resolution and the dynamic-range due to circuit saturation. He concluded that a single output-port followed by a narrow-band receiver might well be sufficient.

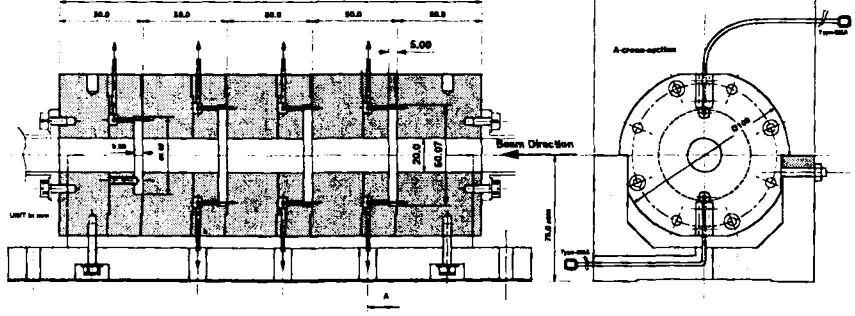

Fig. 1 C-band RF-BPM tested at FFTB. Three BPM cavities and one phase reference cavity were assembled in one block.

However, one problem is that undamped cavities are certain to cause beam break-up with multi-bunch beam at high frequency linear collider design. We can avoid this problem by damping the TM110 mode, but the common-mode rejection by frequency discrimination becomes worse, because the BPM signal after the narrow-band filter becomes lower while the common mode leakage remains at the same level. Therefore, the geometrical cancellation is required, i.e., using diametrically opposite outputs connected to a difference-taking circuit (for example a magic-T). This technique is especially important to develop ultra-high resolution monitor in the range of 1 to 10 nm, where the common mode power can saturate or even brow-up a sensitive head-amplifier, which is prepared to detect extremely small BPM signal from a beam running very close to cavity axis.

Early 1990's, VLEPP group proposed a BPM system to measure a very small beam displacement in nm range for single bunch operation in VLEPP [11]. A special BPM cavity was made to eliminate the common-mode power, however no experimental test was made with beam about this proposal due to financial difficulties happen in Russian laboratories.

At the same period, CLIC project at CERN developed a new BPM system using 30 GHz TM110 mode of a cylindrical resonant cavity, based on W. Schnell's proposal [10]. A high degree of common mode rejection is obtained by symmetry discrimination in the magic T's, and by the use of a narrow-band detection system [12]. Antenna measurements of a brazed test BPM have shown that the electrical center and the mechanical reference surface can be aligned with an accuracy better than 5 μm. They tested this BPM using a 50 MeV, 1 nC single bunch beam at CTF: CLIC test facility. Two BPMs were used to eliminate correlated beam jitter. An upper limit of resolution of +-4 μm has been demonstrated [13].

In order to demonstrate the ultimate resolution in the range of 1 to 10 nm, three-BPM scheme as shown in Fig. 1 was tested at Final Focus Test Beam (FFTB) in 1995. Using 47 GeV electron beam, the spatial resolution of 25 nm for 1 nC single bunch was observed [14]. Some details are described in Sec. 4.

3. Basic Operating Mechanism of Cavity RF-BPM

Fig. 2 shows a simplified diagram of the cavity RF-BPM. When a bunched beam passes through the BPM cavity, it excites the TM110 mode, whose amplitude is proportional to the beam displacement y and the charge q.

Two pickup antennas are used for position detection. The common mode power is canceled in the magic T, and its residual leak is cut off with the band-pass filter. The BPM signal is rectified in the synchronous detector using a mixer, which provides bi-polar output linearly proportional to the beam displacement of y. The phase reference from the reference cavity is fed into the LO-port of the mixer and its phase is adjusted so as to maximize the BPM signal. In this setup, the mixer

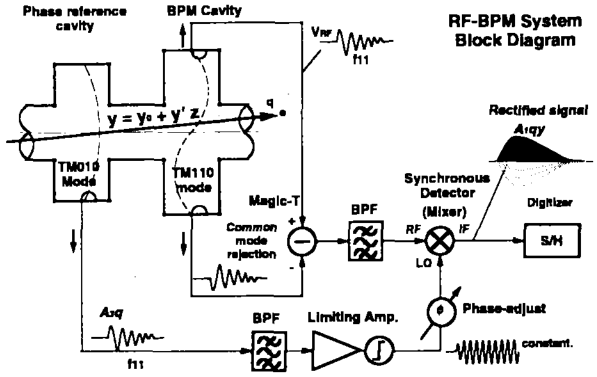

Fig. 2. Simplified RF-BPM Diagram.

eliminates the 90-deg. out-of-phase components such as the common-mode and beam angle signal.

To ensure the linearity in the mixer, the amplitude level of the phase reference signal is kept constant via a limiting amplifier, so that the rectified pulse height is linearly proportional to the bunch charge and the beam displacement: $V \sim A_1 q y$. Where A_1 is a constant, which has to be calibrated by using a low-level signal simulating a beam, or by moving the BPM-cavity on a mechanical mover for a known amount of displacement: Δy. Since the factor A_1 depends on a cable loss and circuit gain, such calibration process is always required at least once at the beginning of machine setup. This is one drawback point of the cavity BPM.

4. Beam Test of C-band RF-BPM at FFTB

In order to demonstrate the high potentiality of the cavity RF-BPM, three cavity BPMs as shown in Fig. 1 was tested with beam at the FFTB. The cavity dimensions and its electrical parameters are summarized in Table-1. The BPM cavity was installed at the image-focus point in the FFTB line, and single bunch electron beam at 47 GeV energy was injected at 30 Hz repetition rate. The beam positions in each cavity centers were measured simultaneously in each pulse. Eliminating the

Table-1 C-band RF-BPM Parameter

Single bunch charge in FFTB: q	~ 1 nC
TM110 frequency: f_{11}	5712 MHz
Cavity radius : a	30.0 mm
Cavity length : l	5.0 mm
Beam hole diameter : D	20.0 mm
Effective cavity length : l_e	25 mm
Cavity-to-cavity distance : L	50 mm
Loaded Q factor : Q_e	130
Circuit shunt-impedance : $(R/Q)_{11}^{cir.}$	22 Ω
Longitudinal impedance : $(R/Q)_{11}^{l}$ (numerical simulation by MAFIA)	410 $k\Omega/m^2$ (502 $k\Omega/m^2$)
Induced voltage in the cavity: V_{11}	120 μV/nC/nm
BPM signal output into 50 Ω: V_{50}	16 μV/nC/nm
Band-pass filter : ΔB	50 MHz
Thermal noise into 50 MHz : V_N	7 μV
Theoretical resolution : Δy	6 nm
Observed resolution at FFTB	25 nm

correlated beam position and angle jitters from these data, we found the position resolution of the BPM to be 25 nm.

The theoretical resolution for an ideal setup is 0.6 nm assuming the noise figure of 3 dB in the head-amplifier. In the practical setup, by including the signal losses of cables, magic-T, filter, attenuator, mixer and waveform shaping loss in filters, the total signal loss becomes –20 dB, thus, the expected resolution becomes 6 nm. The observed resolution is four times larger than the theoretical estimation. A possible explanation is that the common-mode leakage power drives the circuit components at substantial level, which results in mixing the position and common-mode signals due to enhanced non-linearity in the mixer. Further studies will be necessary to understand this problem. The experimental details are reported by T. Slaton [14].

5. Understanding Beam Induced Signal

In this section, we will study the electrical performance of the BPM cavity using simple analytical model and apply to the C-band RF-BPM of Fig. 1.

When a bunched beam of charged particle (electron/positron/etc) runs through the BPM cavity, it generates various EM modes, which are formalized as

$$V_{RF} = A_1 qy + jA_2 qy' + jA_3 q + V_N \qquad (1)$$

where,

$A_1 qy$: Beam position signal, which is the in-phase component of TM110 mode.

$jA_2 qy'$: Beam angle signal, which is 90 degree out-of-phase from the beam current.

$jA_3 q$: Common mode leakage of TM010 mode through the band-pass filter.

V_N : Thermal noise in the detector circuit.

We assume a system using one pick-up antenna followed by a band-pass filter. The magic-T will be introduced later. In this equation, basically the noise signal limits the spatial resolution of the BPM system, while the common-mode signal causes an electrical zero-point shift. It also causes saturation of the head amplifier and limits the dynamic-range. The second term in the equation is the TM110 signal generated by the beam angle, which will provide an useful information of dy/dz, if we use it. In commonly used beam optics, the signal level of the beam-angle is usually much smaller than the beam-position signal, hence we may not worry about it.

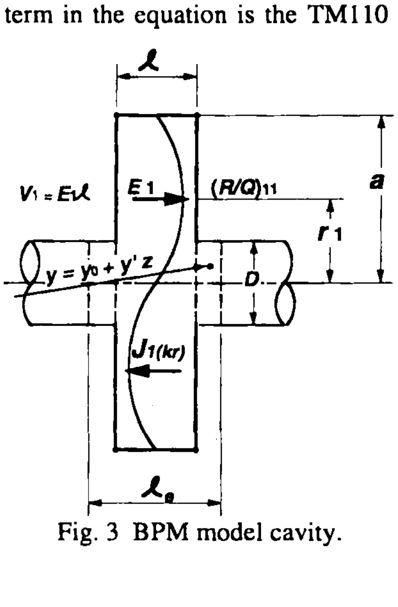

Fig. 3 BPM model cavity.

Each component will be discussed in detail.

5.1 $jA_1 qy$:TM110 beam position signal.

We consider the BPM cavity as shown in Fig.3, and approximate the boundary condition as a closed pillbox for simplicity. The field of TM110 mode can be described by Bessel function as follows.

$$E_z = AJ_1(k_{11}r)\cdot\cos\phi \qquad (2a)$$

$$H_r = -\frac{jA}{\omega\mu}\cdot\frac{J_1(k_{11}r)}{r}\cdot\sin\phi \qquad (2b)$$

$$H_\phi = -\frac{jA}{\omega\mu}\cdot k_{11}J_1'(k_{11}r)\cdot\cos\phi \qquad (2c)$$

where $A = E_1/J_1(k_{11}r_1) = E_1/J_{1.\max}$. k_{11} is the wave-number at TM110 resonance frequency, $k_{11} = \rho_{11}/a$, and $\rho_{11} = 3.832$ is a root of Bessel's function. The resonance frequency is given by $f_{11} = \rho_{11}c/2\pi a = 0.61c/a$. E_1 is the maximum electric field at $r = r_1$, $k_{11}r_1 \approx 1.9$, and the peak value of the Bessel's function is $J_{1.\max} \approx 0.58$. We define the cavity voltage by a simple line integral of the electric field at $r = r_1$,

$$V_1 = E_1 \cdot l . \qquad (3)$$

We calculate the excitation voltage by a beam running in parallel to the cavity axis at displacement of y . From the energy conservation law, equating the work done by the beam and increase of EM stored energy in the equivalent capacitance, we obtain the excitation voltage as

$$\Delta V_{11}(y) = \frac{1}{C_{11}V_1}\cdot\int_{-\infty}^{+\infty} q\mathbf{E}\cdot\mathbf{v}dt$$

$$= q\omega(R/Q)_{11}^{cir.}\int_{-\infty}^{+\infty} E_z e^{jkz}dz/V_1$$

$$= q\omega(R/Q)_{11}^{cir.}\cdot T(\theta_e)\cdot\frac{J_1(k_{11}y)}{J_{1.\max}} \propto y \qquad (4)$$

where, $(R/Q)_{11}^{cir.}$ is the geometrical shunt-impedance defined for the circuit voltage:

$$(R/Q)_{11}^{cir.} = \frac{V_1^2}{2\omega W}$$

$$= \frac{2Z_0}{\pi\rho_{11}}\left(\frac{J_{1.\max}}{J_0(\rho_{11})}\right)^2\cdot\frac{l}{a} = 130\cdot l/a . \qquad (5)$$

$T(\theta_e)$ is the transit-time factor:

$$T(\theta_e) = \frac{\sin(\theta_e/2)}{\theta_e/2} \qquad (6)$$

where θ_e is the transit time defined by $\theta_e = k_{11}l_e$ and l_e is the effective gap length given by $l_e = l + D$, which represents the effect of field leakage into the beam pipe. Z_0 is the intrinsic impedance of vacuum : $Z_0 = 376.7\,\Omega$.

The longitudinal shunt impedance looking from beam can be estimated by replacing the voltage in eq. (5) with beam energy loss:

$$(R/Q)_{11}^{l} = (R/Q)_{11}^{cir.} \cdot T(\theta_e)^2 \left(\frac{J_1(k_{11}y)}{J_{1.\max}} \right)^2 . \quad (7)$$

The output voltage into 50 Ω load is given by

$$\Delta V_{50} = \sqrt{\frac{Z_{50}}{(R/Q)_{11}^{cir.} Q_e}} \cdot \Delta V_{11}(y) \cdot e^{-t/\tau} \cos(\omega t), \quad (8)$$

where $Z_{50} = 50\Omega$. Q_e is the external-Q of the external coupling. The last two terms represent the damping oscillation of impulse response of LCR resonator. The parameter listed in Table-1 was calculated using these equations.

5.2 jA_2qy' :TM110 beam angle signal.

Even if the beam passes the cavity center: $(r,z) = (0,0)$, it can still excite the TM110 mode due to non-zero trajectory angle: dy/dz. Since the beam couples to the electric field of negative polarity at $z < 0$ and the positive polarity at $Z > 0$, the excitation voltage becomes 90 degree out-of-phase from the beam current. This is the reason why the term has j. The excitation voltage can be estimated by integrating the electric field along beam trajectory

$$\Delta V_{11}(y') = \frac{\int_{-\infty}^{+\infty} q\mathbf{E} \cdot \mathbf{v} dt}{C_{11} V_1}$$

$$= q\omega (R/Q)_{11}^{cir.} \int_{-l_e/2}^{+l_e/2} \frac{AJ_1(k_{11}y'z)}{V_1} \cdot e^{-jkz} dz$$

$$\approx jq\omega (R/Q)_{11}^{cir.} \cdot \theta_e \left[T(\theta_e) - \cos\frac{\theta_e}{2} \right] \frac{y'}{J_{1.\max} k_{11} l} . \quad (9)$$

To obtain a clear understanding, we take a ratio to the beam position signal;

$$\frac{\Delta V_{11}(y')}{\Delta V_{11}(y)} = \frac{j}{k_{11} l} \left[1 - \frac{\cos(\theta_e/2)}{T(\theta_e)} \right] \cdot \frac{l_e}{\beta *} \quad (10)$$

We assumed that the electron beam is focused at the center of the BPM cavity, and whose beta-function is β^*. Here we define the "critical beta-function", by which the BPM cavity provide the same signal levels to the beam angle and the beam position. Letting the ratio equal to 1.0, the critical beta-function becomes,

$$\beta_c^* = \frac{l_e}{k_{11} l} \left[1 - \frac{\cos(\theta_e/2)}{T(\theta_e)} \right] \quad (11)$$

In the C-band RF-BPM, $l = 5$ mm, $D = 20$ mm, $l_e = 25$ mm and $\beta_c^* = 37$ mm. In commonly used beam optics, the beta-function is much longer than this value, thus the contribution of the beam angle signal is negligibly small. One exception is the interaction point in a colliding-beam machine, where the beta-function can be smaller, where the beam angle signal dominates.

5.3 jA_3q : Common mode leakage of TM010

Since the TM010 mode does not have a node point at the cavity center, and field pattern is almost flat, electron beam always induces a constant voltage. Hence it is called "the common mode". In case of the linear collider application, the electron beam has to be controlled to pass very close to the cavity center, and the BPM signal of TM110 mode becomes much smaller than the TM010 mode. Therefore, even a very small leak of TM010 mode can deteriorate the BPM accuracy.

The ratio of the TM110 BPM signal to the common mode at each peak is given by

$$\frac{\Delta V_{11}(y)}{\Delta V_{01}} \approx \frac{4\pi}{\lambda_{11}} \cdot y \quad (12)$$

For example, in the C-band BPM, at 10 nm displacement the ratio becomes 2×10^{-6}. In case of the nanometer-resolution BPM design, one should be very careful about the common mode power.

Since the resonance frequency of the common mode of TM010 is far from the BPM TM110 mode, one could imagine the band-pass filter would be enough to eliminate it. This is true in the case of coasting beam. However, in the linear collider, the beam is a single bunch or a multi-bunched beam, and its frequency spectrum is much wide. Therefore, the impedance tail of TM010 mode generates a substantial common-mode signal at the BPM frequency, which easily passes through the band-pass filter and interferes with the BPM signal.

Assuming the bandwidth of the filter: ΔB, the leakage signal can be estimated by

$$\Delta V_{01}^{leak} = \frac{1}{\sqrt{2\pi}} \int_{\omega_{11} - \Delta B/2}^{\omega_{11} + \Delta B/2} I_\omega Z_{com} d\omega \quad (13)$$

Using a simple resonator model, the leak voltage becomes,

$$\frac{\Delta V_{01}^{leak}}{\Delta V_{11}(y)} = j \frac{\lambda_{11}}{4\pi y} \cdot \frac{\Delta B}{\omega_{11}} \quad (14)$$

Note that the common mode leakage does not depend on the Q-factor of the common mode. This is due to that, the TM010-mode impedance becomes pure inductive or capacitive at the BPM frequency, which is not a function of the Q-factor of TM010-mode. Here we define the equivalent displacement of beam against the common mode leak. Letting the ration of eq. (14) to unity,

$$\Delta y_{com}^{leak} \approx \frac{\lambda_{11}}{4\pi} \cdot \frac{\Delta B}{\omega_{11}} . \quad (15)$$

This equation provides useful measure to the common mode leakage power. For example, in the C-band BPM, to achieve the offset less than 1 μm, we need to make the filter bandwidth $\Delta B < 1.4$ MHz. We can develop a narrow-band detector by the super-heterodyne circuit. However, the time response becomes quite slow, it will be at about 1 μsec in this case, hence any details in the bunch train will be averaged. This will be acceptable for the single-bunch application.

However, to observe some structure in a multi-bunch train, we need faster response. To do this, a wide bandwidth circuit will be used, while the common mode leak becomes larger. To reduce the common mode signal, we use a magic-T and the synchronous detection scheme. The equivalent beam displacement becomes

$$\Delta y_{com}^{leak} \approx \frac{\lambda_{11}}{4\pi} \cdot \frac{\Delta B}{\omega_{11}} \cdot (\Delta A_{MgT} \Delta\phi_{ref.} + \Delta\phi_{MgT}), \qquad (16)$$

where

ΔA_{MgT} : Amplitude imbalance error of the magic-T and cable connections.

$\Delta\phi_{ref.}$: Phase error of reference signal in the synchronous detector.

$\Delta\phi_{MgT}$: Phase imbalance of magic-T and cable.

For example, in the C-band BPM case, the bandwidth of the filter was chosen 50 MHz so as to match with the loaded-Q of the cavity. The errors were roughly:

$\Delta A_{MgT} = 0.1$ (-20 dB rejection ratio)

$\Delta\phi_{ref.} = 0.05\,\text{rad}$ (3 degree)

$\Delta\phi_{MgT} = 0.15\,\text{rad}$ (1 mm cable difference)

From eq.(16), the displacement becomes $\Delta y_{com}^{leak} = 6\ \mu\text{m}$. In the FFTB test, we observed a few μm shift of zero point between three BPMs. However, the offset was not constant, and varied with operation conditions. Further experimental studies will be required to obtain a full understanding on the common mode effect.

As seen in eq. (16), the phase error in the magic-T directly causes the zero point error. Only 1mm length difference in two connecting cables causes a substantial offset. To avoid this problem, the author proposed a new BPM-cavity in 1997, which cancels the common mode using a slot coupling inside the cavity. Two BPMs using this idea will be attached to the C-band accelerating structure and its performance will be tested at ASSET [15].

5.4 V_N : Noise signal

The thermal noise in the head amplifier limits the position resolution. The equivalent thermal noise is

$$V_N = \sqrt{4kT\Delta BRN_F} \qquad (17)$$

where k : Boltzman constant,

T : Absolute temperature (K)

ΔB : Bandwidth (Hz)

R : Circuit resistance (Ω)

N_F : Noise figure of head amplifier.

For 50 Ω impedance at room temperature, the noise level becomes

$$V_N = 1 \times \sqrt{N_F}\ \ (\text{nV}/\sqrt{\text{Hz}}) \qquad (18)$$

Here we did not take into account the leakage signal of the RF accelerating field. In case of monitoring a coasting beam, since the beam spectrum becomes line spectrum, we use the RF accelerating frequency or its harmonics as the detection frequency. Therefor we must carefully design the BPM system to eliminate the leakage from the RF accelerating field. However in case of the e+e- linear colliders, a multi-bunch beam with a certain bunch spacing of a few nsec is used. Where, the beam spectrum becomes wide, and we can chose the detection frequency far from the RF-acceleration field, and the narrow-band filter and the synchronous detection circuit will perfectly eliminate the leakage.

6. Conclusion

Theoretical and experimental studies to develop nanometer resolution RF-BPMs are described in this paper. Analytical models on the resolution limit, the beam angle contribution and the center accuracy are presented. The test result of the C-band RF-BPM at FFTB was analyzed on this model. While the measured resolution of 25 nm is still larger than expected, it is the highest resolution ever achieved by any kind of BPMs using single-bunch beam.

For the e+e- linear collider applications, the following R&Ds should be performed.

(1) Development of simple and low cost detection circuit and data handling system.

(2) Capability of monitoring the multi-bunch structure.

(3) Design the cavity structure to optimize the impedance to avoid multi-bunch beam instability, while satisfying the required position sensitivity. ·

(4) Common-mode handling.

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