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LOW Q CAVITY BPM STUDY FOR THE BEAM POSITION MEASUREMENT OF NANOSECOND SPACED ELECTRON BUNCHES *

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Abstract

Low Q cavity BPM is a key to distinguish closely spaced electron bunches allowing precise beam handling for XFEL facilities operating in a multi-bunch mode at high repetition rate up to hundreds MHz. The inter-bunch signal pollution issue becomes significant when bunch separation is down to nanosecond and causes the position detection to be increasingly overestimated. Solely relying on extreme low Q to achieve sufficient decay within bunch interval leads to appreciable interference from non-signal modes due to strong overcoupling of antenna design is required. The error imposed on measured position raises a challenge to meet the goal of high resolution. Alternatively, a concept is proposed to remove the dominant part of signal pollution at the moment of sampling by intentionally shifting the phase of the last bunch signal 90degree respect to that of current bunch signal, where signal sampling is normally taken for nanosecond spaced bunches. This quadrature phase shift is defined by properly choosing the operational frequency of dipole mode regarding to the bunch frequency. A low Q cavity BPM prototype to identify technical challenges and verify this concept is under development in the R&D plan for future XFEL with high repetition rate.

INTRODUCTION

Precise beam handling is critical in X-ray Free-Electron Lasers (XFEL) to guarantee sufficient interaction between an electron beam and x-ray in the self-amplified spontaneous emission (SASE) process of x-ray generation. In the undulator section, the beam must be overlapped with x-ray typically in an order of a few microns for less power degradation compared to an idea case, which requires beam position monitors (BPM) with sub-micron resolution [1-2]. Of all the types, high resolution RF cavity BPMs are widely employed other than button BPMs, stripline BPMs, etc. Low loaded quality factor (Q) of cavity BPM with broad bandwidth is generally intended to allow individually detecting beam position in multi-bunch operations, where bunches are closely spaced. Cavity BPMs with Q of 40 used in Swiss-FEL significantly reduce inter-bunch signal pollution with 28 ns bunch separation [3], which otherwise causes measured position to be overestimated if without sufficient decay. The residual signal excited by the previous bunch at the moment of current bunch arrival decays to be less than 0.1%. Upon the consideration of multi-bunch operation in the future, the quality factor of 4.76GHz cavity BPMs in SACLA were designed at 52, corresponding to a decay time of 3 ns [4].

The inter-bunch signal pollution issue becomes significant when bunches are spaced only several ns. An R&D plan aiming to identify key technical challenges for future hard XFEL with high repetition rate and high photon energy has been carried out in Chinese Academy of Engineering Physics (CAEP). The requirement on beam position detection is specified at sub-micron resolution in space and 2.3ns in time domain. A lower Q cavity BPM design is a straightforward way to distinguish 2.3ns spaced bunches. To achieve 1% residual of the previous bunch signal decaying within 2.3ns, Q of 7.5 is required, assuming the same frequency 4.76GHz with SACLA cavity BPM. The interference from non-signal modes due to such broad loaded bandwidth (635MHz) in the frequency domain, however, imposes appreciable errors into the measured position signal and raises a challenge to meet the goal of sub-micron resolution.

Alternatively, we propose a concept of eliminating the dominant part of signal pollution at the moment of signal sampling. For practical concern on electronics, signal sampling in a time window of 2.3 ns is taken only at peak. The last bunch signal is intentionally shifted by 90 degree with respect to the current bunch signal. The residual signal of the last bunch that represents the dominant part of signal pollution exactly varies to zero on a sinusoidal trace at the sampling time of the current bunch signal. The phase shift is realized by properly choosing the frequency of signal mode regarding to the bunch repetition frequency. Verification of this concept is enrolled in the R&D plan. Under the collaboration with the beam instrumentation team of SINAP, development of a low Q cavity BPM prototype has been carried out. This paper presents a description of the concept to address the specific issue of inter-bunch signal pollution and simulation results of the cavity BPM prototype.

INTER-BUNCH SIGNAL POLLUTION

The principle of position detection in cavity BPMs is referred to the excitation of dipole mode whose response is proportional to the beam displacement. Including time variation, the output voltage of the excited dipole mode is given as,

$$V_{out} = A_0\, x\, sin(2\pi f_d t)\, e^{-t/\tau} \tag{1}$$

where f_d is the dipole mode frequency, A_0 is a proportionality constant, x is the beam displacement and τ is the characteristic decay time. τ is determined by Q and f_d,

$$\tau = Q/\pi f_d \tag{2}$$

The term f_d/Q is referred to the bandwidth. Broad bandwidth leads to fast response of system. The residual signals

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from previous bunches introduce error to the detection of current bunch position. The portion from the last bunch is dominant in the scope of low Q cavity BPM. Figure 1 shows the last bunch signal after decaying in 2.3 ns under different bandwidth. To maintain a residual level within 1%, the bandwidth has to be broad as 635MHz. A low Q cavity BPM with loaded quality factor about 7.5 is needed if we choose a C-band frequency, for instance, 4.76GHz. Strong overcoupling of pickup antenna has to be designed since here Q is determined by the external quality factor of the output port. The rejection of non-signal modes becomes less efficient even though coupling slots are employed. The tail of the monopole mode response in the frequency domain can be significant at the dipole mode frequency. The error imposed to the position detection on account of the monopole signal leakage raises a challenge to meet the goal of sub-micron resolution.

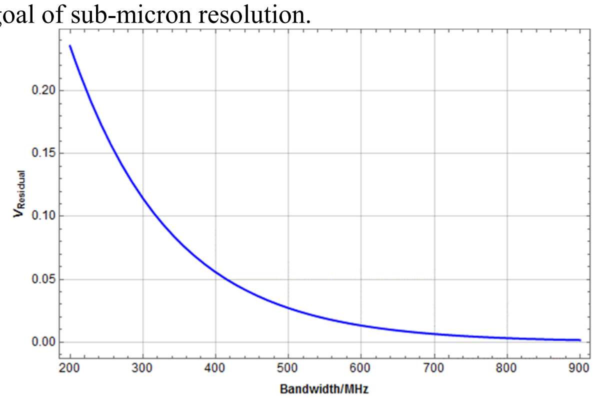

Figure 1: Residual signal (relative amplitude) at the arrival of the current signal at a given bandwidth.

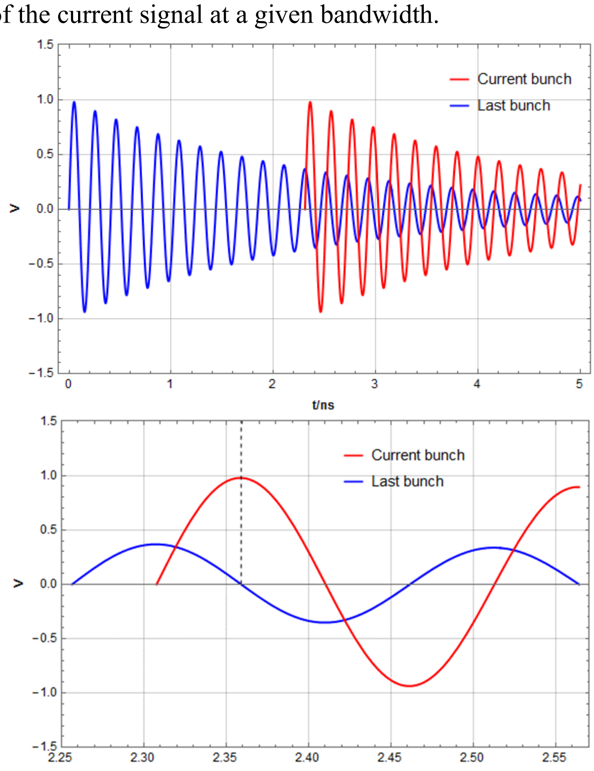

Figure 2: Time evolution of the last bunch signal and the current one, the dashed line in the down plot marks the sampling time of the current bunch signal.

Rather than shifting all the efforts into the design of an extreme low Q cavity BPM, alternative measure to address signal pollution issue has to be resorted. In a short time window of 2.3 ns for digital processing, output signal has to be sub-sampled only at the peak for each bunch due to practical concern on electronics. The last bunch signal is intentionally shifted by 90 degree with respect to the current bunch signal. The residual signal of the last bunch that represents the dominant part of signal pollution exactly varies to zero at the sampling time of the current bunch signal (Figure 2). Choosing f_d regarding to the bunch repetition frequency (f_b) in a relation of $f_d = (n + 0.25)f_b$, where n is harmonic number, results in a quadrature phase shift. $f_d = 4.875\text{GHz}$ was determined in the prototype design, corresponding to n=11. The residual of the second last bunch then turns to be dominant. Figure 3 shows the requirement on Q is loosened. 1% residual corresponds to Q=15.3, which is achievable as shown in the simulation results of the prototype in the next section. For comparison, up to 10% of residual might exist at the same bandwidth if an exact harmonic of bunch frequency is chosen.

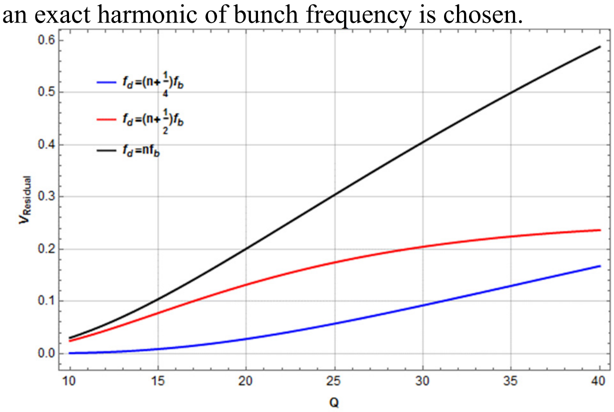

Figure 3: Dominant part of residual signal varying with Q. The cases for other relations between f_d and f_b are included as well.

SIMULATION RESULTS

The design of a cavity BPM at frequency of 4.875GHz has been done under the collaboration with beam instrumentation team of SINAP. Electromagnetic simulation using CST [5] based on Shintake design was carried out in parallel both at Institute or Fluid Physics (IFP) and SINAP. The position of pickup antenna was adjusted towards the coupling slots to meet the goal of 300MHz bandwidth. However, the coupling to these non-signal modes is increased as well. Suppression of the interference from non-signal modes, including monopole and dipole-like mode, was primarily concerned during optimization. The dipole-like mode is resonating mostly in either pair of coupling waveguides but with higher frequency than the working mode and responses in a similar way. Thus, it is also strongly coupled out by antennas, which causes a parasitic peak appeared alongside the working mode. The optimized results are shown in Figure 4Figure 7. SINAP design indicates better suppression on the dipole-like mode, while the rejection to monopole mode is seen in IFP design. Table 1

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lists the key parameters of both designs. SINAP design has been taken for prototype fabrication.

Table 1: Key Parameters of Both Designs

Position cavity	IFP	SINAP
Dipole mode [GHz]	4.875	4.875
Loaded Q	15.9	15.4
R/Q [Ω/mm^2]	0.54	0.445
Voltage at output port [mV/um/nC]	14	12.4
Monopole mode [GHz]	3.726	3.885
External Q at one port	9.8e10	9.04e9
Estimated error on position [um]	0.14	0.4
Reference cavity		
Monopole mode [GHz]		4.875
Loaded Q		13
Voltage at output port [V/nC]		120

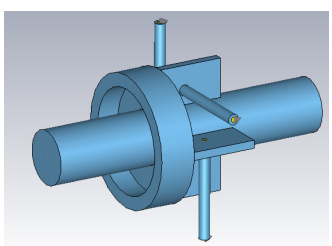

Figure 4: Position cavity of IFP design.

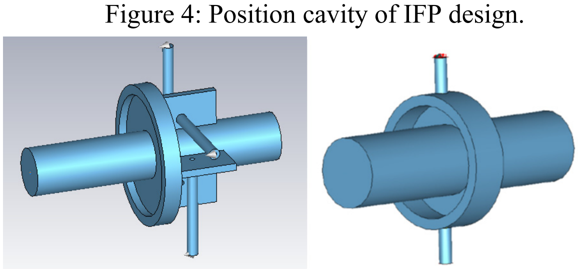

Figure 5: Position cavity (left) and reference cavity (right) of SINAP design.

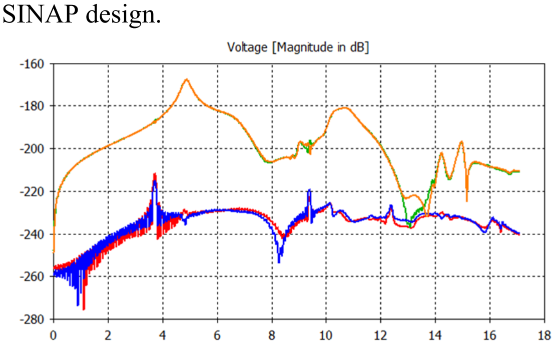

Figure 6: Frequency responses of the signals from 4 output ports (IFP design).

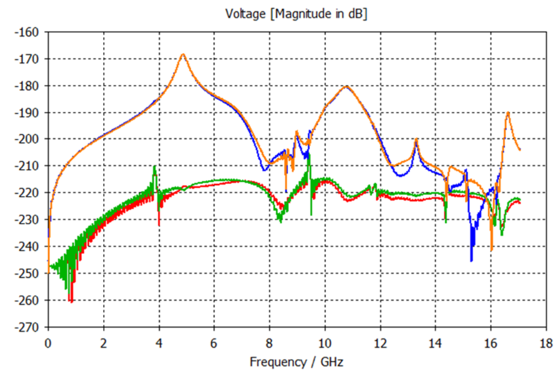

Figure 7: Frequency responses of the signals from 4 output ports (SINAP design).

SUMMARY

The issue of inter-bunch signal pollution is concerned for beam position measurement of XFEL in operations of multi-bunch closely spaced by several ns. A concept of minimum signal pollution at the sampling time is proposed to loosen an extreme low Q requirement for sufficient decay of residual signal from previous bunches, which leads to appreciable interference from non-signal modes due to strong overcoupling of antenna design is required. The residual signal from the last bunch representing the dominant contribution can be eliminated from the detection during signal sampling by means of quadrature phase shifting. 1% residual is achievable with a moderate low Q required for suppression the residual from the second last bunch, which has been verified in prototype design of the low Q cavity BPM for the R&D plan at CAEP.

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