# Conditioning of BPM pickup signals for operations of the Duke storage ring with a wide range of single-bunch current [*]

XU Wei(徐卫)[1,2;1)]    LI Jing-Yi(李京祎)[1,2;2)]    HUANG Sen-Lin(黄森林)[3]    W. Z. Wu[2]    H. Hao[2]
P. Wang[2]    Y. K. Wu[2]

[1] National Synchrotron Radiation Laboratory (NSRL), University of Science and Technology of China, Hefei 230029, China
[2] Dept. of Physics, Duke University and FEL lab, Triangle Universities Nuclear Laboratory, Durham, NC 27708-0308, USA
[3] Institute of Heavy Ion Physics, Peking University, Beijing 100871, China

**Abstract:** The Duke storage ring is a dedicated driver for the storage ring based oscillator free-electron lasers (FELs), and the High Intensity Gamma-ray Source (HIGS). It is operated with a beam current ranging from about 1 mA to 100 mA per bunch for various operations and accelerator physics studies. High performance operations of the FEL and γ-ray source require a stable electron beam orbit, which has been realized by the global orbit feedback system. As a critical part of the orbit feedback system, the electron beam position monitors (BPMs) are required to be able to precisely measure the electron beam orbit in a wide range of the single-bunch current. However, the high peak voltage of the BPM pickups associated with high single-bunch current degrades the performance of the BPM electronics, and can potentially damage the BPM electronics. A signal conditioning method using low pass filters is developed to reduce the peak voltage to protect the BPM electronics, and to make the BPMs capable of working with a wide range of single-bunch current. Simulations and electron beam based tests are performed. The results show that the Duke storage ring BPM system is capable of providing precise orbit measurements to ensure highly stable FEL and HIGS operations.

**Key words:** beam position monitor, signal conditioning, closed orbit feedback, storage ring FEL

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## 1    Introduction

The Duke storage ring is a dedicated driver for the storage ring based free-electron lasers (FELs) [1], and the High Intensity Gamma-ray Source (HIGS) [2]. The high intense γ-ray beam is produced by colliding the high energy electron beam with a high power FEL optical beam inside the FEL cavity. The electron beam orbit in the storage ring not only impacts the beam injection and beam lifetime, but also, especially in the FEL straight section which hosts the optical klystron FEL, determines the quality of the FEL lasing and impacts the flux of the γ-ray beam [3, 4]. Maintaining a good electron beam orbit is essential for high performance operations of the Duke light sources.

The electron beam orbit in the Duke storage ring is measured by the beam position monitors (BPMs). This system was first brought into operation in 1998 [5]. In the early days, the BPM measurement had been found to be strongly dependent on the single-bunch current. Investigations showed that this effect was the result of an overloading of the BPM electronics modules due to the high peak voltage associated with a large single-bunch current. By employing cables with high loss in the GHz region, the peak voltages were reduced, and the BPMs were able to provide reasonably good orbit measurements for a single-bunch current ranging from 0.5 to 20 mA [6].

In 2006, a major upgrade of the light source facility was completed. In the upgrade, a booster synchrotron was constructed as the full-energy injector of the storage ring [7]. In addition, the north straight section of the storage ring was overhauled for a new injection scheme and for hosting a new high-order mode (HOM) damped RF cavity [8, 9]. In 2008, another key system of the storage ring, the longitudinal bunch-by-bunch feedback (LFB) system, was installed and commissioned for routine user operations [10, 11]. Benefiting from all of these upgrades, the single-bunch current threshold of the stor-

age ring was significantly increased. For example, a 95 mA electron beam was stored in the storage ring at 600 MeV in the single-bunch mode with FEL lasing. In the two-bunch HIGS operation mode, the storage ring can be operated with a total beam current up to 120 mA, or 60 mA in each bunch. In these cases of high bunch-current operations, the BPM electronics modules would have fully saturated without additional signal conditioning, and were not able to perform meaningful orbit measurements [12]. Furthermore, the high single-bunch current produces a very high peak voltage on the BPM pickup, which could potentially damage the BPM electronics.

On the other hand, some operations need a low electron bunch current. For example, some experiments need a small γ-ray beam energy spread, which is usually realized by running a high-current bunch and a very low-current bunch which does not produce FEL lasing. Some machine studies also need a low beam current, which sometimes is even lower than 1 mA. In order to obtain a precise measurement of the electron beam orbit in a wide range of a single-bunch current from about 1 mA to 100 mA, the RF pickup signal must be conditioned to increase the BPM's dynamic range.

Low pass filters (LPFs) have been widely used in BPM signal conditioning. The purpose of this paper is to present a method using LPFs to increase the dynamic range of the BPMs of the Duke storage ring to maintain the high performance of the storage ring and provide highly stable aiming of the γ-ray beam. A preliminary study has been reported in a conference paper [12]. This paper first reports the measurements of two types of BPM pickups, button and stripline pickups which are used in the Duke storage ring. Then, it describes the details of the pickup signal conditioning. The dependency of the BPM readings on the bunch current is measured and reported in the later part of this paper.

## 2　A revisit of BPM pickup signals

Let us consider a relativistic electron bunch with a longitudinal Gaussian distribution of its charges circulating in a storage ring. The beam current is periodic and can be written in the time and frequency domains as [11],

$$
I_{\mathrm{b}}(t) = \frac{I_0 T_0}{\sqrt{2\pi}\sigma_\tau} \sum_{n=-\infty}^{\infty} \mathrm{e}^{\frac{-(t-nT_0)^2}{2\sigma_\tau^2}},
$$

$$
I_{\mathrm{b}}(\omega) = I_0 \sum_{m=-\infty}^{\infty} \mathrm{e}^{\frac{-(\omega-m\omega_0)^2}{2\sigma_\omega^2}},
$$
(1)

respectively, where $I_0$ is the averaged beam current, $\sigma_\tau$ is the RMS bunch length in the time domain, $\sigma_\omega = 1/\sigma_\tau$ is the RMS spectral width, $T_0$ is the revolution time of the

electrons, $\omega_0 = 2\pi/T_0$ is the angular revolution frequency, $n$ is the turn number, and $m$ is the harmonic number of the revolution frequency. Eq. (1) indicates that an electron beam with a short bunch length has a very wide spectrum in the frequency domain. As an example, the natural RMS bunch length of an electron beam with the energy of $E_{\mathrm{b}}=1$ GeV and RF voltage of $V_{\mathrm{RF}}=850$ kV in the Duke storage ring is 2.0 cm [13], its spectrum in the frequency domain is comprised of a rich set of frequency responses from the DC to GHz region.

The electron beam can be measured by BPM electrode pickups with a proper grounding. Interacting with the electromagnetic field associated with the electron beam, the electrode pickups can be used to measure the electron beam current and position. Following the reports presented by G. R. Lambertson and D. A. Goldberg on electromagnetic detectors [14, 15], we revisit the signals from two types of BPM pickups, button and stripline pickups, which are used in the Duke storage ring.

The measured pickup signal can be described by

$$
V = Z_{\mathrm{T}} I_{\mathrm{b}},
$$
(2)

where $Z_{\mathrm{T}}$ is the transfer impedance of the pickup. A button pickup is an isolated plate on the wall of the vacuum chamber. Compared to the electron bunch length, the size of the plate is usually small. It has a dominant capacitive coupling and is typically modeled with an equivalent RC circuit. When an electron bunch passes the plate, the capacitor experiences charging and discharging processes, the voltage across $R$ is given by [14, 15],

$$
V(\omega) = \mathrm{j}gl \frac{\omega}{\beta c} \frac{R}{1+\mathrm{j}\omega RC} I_{\mathrm{b}}(\omega),
$$
(3)

and the transfer impedance of a button pickup is [14, 15],

$$
Z_{\mathrm{T}}^{\mathrm{button}}(\omega) = \mathrm{j}gl \frac{\omega}{\beta c} \frac{R}{1+\mathrm{j}\omega RC},
$$
(4)

where $R$ is the resistance of the circuit, $C$ is the capacitance of the button pickup, $l$ is the effective length of the button, and $g$ represents the ratio of the image charge on the plate to the total image charge and is sensitive to the beam position.

A stripline pickup is a long plate with one end grounded on the wall of the vacuum chamber, and the other end connected to the processing electronics via an output line. The grounded end is usually in the downstream to the electron beam motion. In this case, when an electron bunch arrives in the upstream end of the stripline, a signal is coupled into the electrode and divided into two parts – one part moves toward the output line and the other part moves toward the downstream end. When the electron bunch leaves the downstream end, a signal with an opposite polarity is generated. After canceling the signal from the upstream, the signal

moves toward the output line. Assuming the electrons and the excited signals both move with the speed of light $c$, there are two pulses moving through the output line separated by $\Delta t = 2l/c$, where $l$ is the effective length of the stripline. Also assuming the electrode characteristic impedance and the output line impedance are $Z_{\rm L}$, the signal can be written as [14, 15],

$$V(t) = \frac{1}{2} g Z_{\rm L} \left( I_{\rm b}(t) - I_{\rm b}\left(t + \frac{2l}{c}\right) \right). \tag{5}$$

By Fourier transform, we can get the stripline's transfer impedance [14, 15],

$$Z_{\rm T}^{\rm stripline} = g Z_{\rm L} {\rm e}^{{\rm j}(\pi/2 - kl)} \sin(kl), \tag{6}$$

where $k = \omega/c$ is the wave number of the signal. When $kl = \pi/2$, i.e. $l = \lambda/4$, $Z_{\rm T}^{\rm stripline}$ is a real number, and its amplitude reaches maximum. For this reason, this type of stripline BPM is sometimes called a quarter-wave loop device.

Equations (2), (4) and (6) indicate that the spectrum of a BPM pickup signal is determined by both the spectrum of the electron beam and transfer impedance of the pickup electrode.

## 3    The Duke storage ring BPM system

The racetrack-shaped Duke storage ring is comprised of two arcs, the east arc (EARC) and west arc (WARC), and two 34 m long straight sections, the north straight section (NSS) and south straight section (SSS). The storage ring driven oscillator FEL is located in the SSS. The NSS hosts the injection kickers, RF cavity, LFB kicker, and other beam measurement systems. The arc lattice is comprised of ten FODO cells, including eight regular cells and one modified cell at each end [13]. Due to the space limitation, the sextupole magnets were removed from the original design in the arc, and the sextupole magnetic fields were realized by shifting the magnetic centers of the quadrupole magnets horizontally inward by about 2.5 mm [16]. Consequently, this arrangement makes the electron beam have a large horizontal offset at the locations of the arc BPM pickups, causing them to have a significant nonlinear response to the beam orbit offset.

Thirty-three BPMs are currently used to measure the electron beam orbit around the storage ring. Three types of electrodes, 30.4 mm long striplines (named LSL), 21.6 mm long short striplines (named SSL) and buttons with a 5.0 mm diameter, are used as BPM pickups. They

Table 1.    The distribution of the 33 BPM pickups in the Duke storage ring.

|  | east arc | west Arc | NSS | SSS |
|---|---|---|---|---|
| # of LSL | 0 | 0 | 6 | 0 |
| # of SSL | 9 | 9 | 0 | 2 |
| # of button | 0 | 0 | 1 | 6 |

are distributed around the storage ring as shown in Table 1.

Besides being used in the global orbit feedback, some BPMs in the SSS are also used to allow local adjustments of the electron beam orbit to optimize the FEL lasing and γ-ray beam production of the HIGS.

The Bergoz multiplexer BPM modules are used to process the pickup signals [17]. An on-board 1 GHz low pass filter (LPF) is used for each of the four RF inputs to protect the module from being damaged by very short, high voltage pulses. After the LPFs, the signals are time-multiplexed into a superheterodyne receiver, and then fed through a band-pass filter (BPF), which defines the operation range of the module. Only those signal harmonics in the operation range are used for processing the orbit information [17]. The operation range of the Duke storage ring BPM modules is 178.55±20 MHz, which is close to the frequency of the RF system.

A VME-based 64-channel 16-bit ADC board is used to digitalize the orbit signal from the output of the BPM modules. The orbit measurement system is a part of the control system, which is based upon the Experimental Physics and Industrial Control System (EPICS) [18]. The orbit data can be accessed via EPICS channel access (CA) at a rate of 10 Hz or higher.

Low loss Heliax cables were originally used for connecting the BPM pickups and electronics modules. It was found that the BPM modules were highly overloaded with this arrangement. RG223-U cables with higher loss in the GHz region were then used instead. This enables the BPMs to provide reasonably good orbit measurements for a single-bunch current ranging from 0.5 to 20 mA. For a single-bunch current higher than 20 mA, most BPMs cannot provide precise measurements, and the pickup signals need to be further conditioned.

## 4    BPM pickup signal conditioning

In order to learn about the properties of the pickup signals, the time domain and frequency domain signals of the pickups are studied in this section.

### 4.1    The time domain signals

The beam signal from the BPM pickup is comprised of a series of very short pules in the time domain, and thus has a very wide spectrum in the frequency domain. In order to measure enough details of the signal in the time domain, a digital oscilloscope, Tektronics TD7404 digital oscilloscope with a 4 GHz bandwidth and up to 20 GHz sampling rate, is used to measure the BPM pickup signals. A 60-feet long RG223-U cable is used to connect the BPM pickup and the oscilloscope. To protect the oscilloscope from high peak voltage, proper broadband attenuators are used to bring the signal to

a reasonable level. The signals from each of the three types of the pickups are measured as a function of single-bunch beam current. As an example, a set of LSL pickup signals measured as a function of the single-bunch beam current are shown in Fig. 1(a). The ringing pattern of the signal is caused by the RF filtering of the cable. The peak voltages of BPMs from different sectors of the Duke storage ring, N11, W16 and S02 which are LSL, SSL and button BPMs respectively, are shown as a function of the single-bunch current in Fig. 1(b).

According to the manufacture's specifications, in order to make the BPM module work properly and avoid electronic damage from high peak voltages, the signal level after the 1 GHz on-board LPF of the Bergoz BPM electronics module should be lower than 5 volt [19]. To estimate the peak voltage after the on-board LPF, the measured time domain signal is processed using a 1 GHz digital LPF. The results show that the peak voltage after the digital LPF would exceed 5 volts around 6 mA for LSL BPMs and 13 mA for SSL BPMs. Assuming the

peak voltage is proportional to the single-bunch current, by extrapolating the data of the button pickup signal, the peak voltage of button BPMs reaches 5 volts around 52 mA, see Fig. 1(b). This means in order for the BPM system to work at a single-bunch current up to 100 mA, all BPM pick signals must be properly conditioned to reduce their peak voltages.

## 4.2 Spectrum power distribution

As discussed in the previous sections, the power of the pickup signal is distributed in a very wide range in the frequency domain. The power spectrum is determined by the characteristic impedance of the pickup for a given beam signal. To understand the spectral power distribution, the spectra of the pickup signals are measured using an HP 8563E spectrum analyzer. Fig. 2(a) shows a measured spectrum of the signal from one of the LSL pickups. This figure indicates that only a very small portion of the signal power is in the BPM's frequency
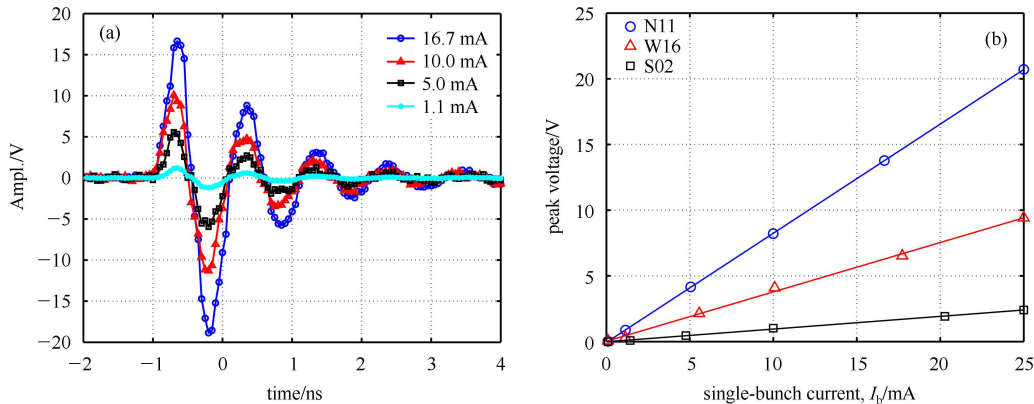


Fig. 1. (color online) Time domain BPM pickup signals. (a) Time domain signals of an LSL electrode measured at different single-bunch currents. (b) Peak voltages of the BPM pickup signals. The circles, stars and squares are peak voltages obtained from the measured signals after applying a 1 GHz LPF. The lines show the linear fits. Measurements for all three types of BPMs (LSL, SSL, and button) are shown with three BPMs from different sectors of the storage ring (N11, W16, and S01, respectively.)
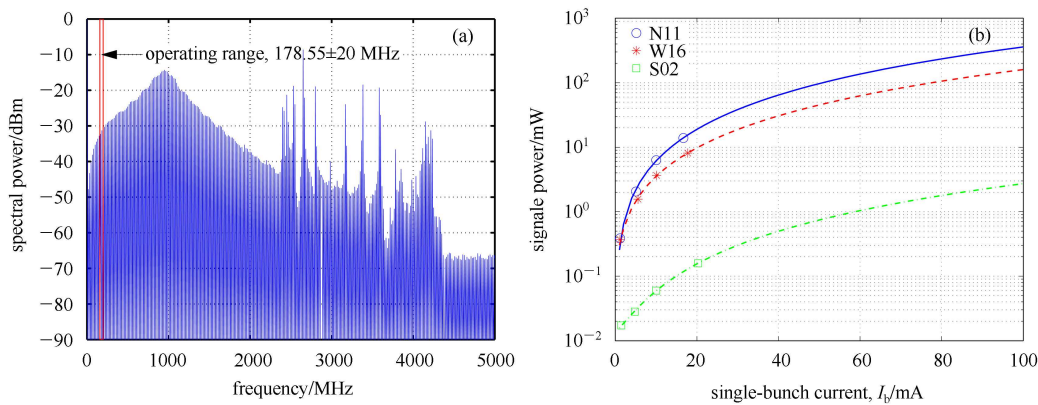


Fig. 2. (color online) BPM pickup signals in the frequency domain. (a) A spectrum of an LSL pickup signal. This spectrum is measured after a 60 feet long RG223-U cable. (b) The total spectrum power as a function of the single-bunch current.

operation range, 178±20 MHz. In Fig. 2(b), the measured and projected total spectral power of all three types of pickups are plotted as a function of the single-bunch current. The projected total powers at 100 mA of these pickups are listed in Table 2. Table 2 also lists the ratios of the power in the BPM's operation range to the total power for a 20 mA single-bunch beam.

Since only those revolution harmonics in the frequency operation range are actually used for beam position processing, removing other harmonics by a proper BPF would have no significant adverse impact on the beam position measurement. Because the operation frequency of the Duke storage ring BPM is relatively low, an LPF can also do the job as a BPF. After removing unused harmonics in the high frequency region, the signal pulse length in the time domain is increased, the total power of the signal is reduced, and hence the peak voltage is reduced.

Table 2.  The spectrum power of the pickup signals.  $P_{100}$ is the projected total power of a 100 mA single-bunch current.  $P_{20}$ and $P'_{20}$ are the measured total power and the power in the BPM's operation range, $178 \pm 20$ MHz, of a 20 mA single-bunch current, respectively.

|  | LSL | SSL | button |
|---|---|---|---|
| $P_{100}$/mW | ∼360 | ∼160 | ∼3 |
| $P'_{20}/P_{20}$ | 0.2% | 0.2% | 0.8% |

### 4.3   Simulation on the signal conditioning

To get a better understanding of the pickup signal conditioning using LPFs, simulations using measured time domain signals and LPFs' insertion losses are performed.

The Duke storage ring has been operated with a variety of modes and bunch patterns. Its single-bunch current varies by two orders of magnitude to meet the requirements of various user programs.

To work with a high beam current, the filters used for the signal conditioning must have a high input power threshold. Low insertion losses around 178 MHz are essential to enable the BPM electronics to work with a low beam current. With careful research on the commercially available filters, two types of Mini-circuits LPFs, VLF-160 and VLF-320, are found to best meet these requirements [20, 21]. Their input power thresholds are higher than 3 W. The cut-off frequency (3 dB) of VLF-160 and VLF-320 LPFs are around 236 MHz and 460 MHz, respectively. Both of them have a small insertion loss around 178 MHz, the operation frequency of the BPM electronics.

Using the manufacturer's specifications on insertion loss and the measured time domain signals, simulations are performed to evaluate the peak voltage reduction.

In these simulations, the measured time domain data are transformed to the frequency domain using the fast Fourier transform (FFT) to obtain the power spectrum. After applying the frequency filtering and power loss characteristics of the LPFs to the power spectrum, the frequency domain signal is transformed back to the time domain using the inverse FFT. The peak voltage is calculated using the processed time domain data. Fig. 3 shows the calculated peak voltage as a function of the single-bunch current for all three types of BPM pickups. By extrapolating these curves, the peak voltages associated with a 100 mA single-bunch current are calculated and tabulated in Table 3.

These values are computed based upon the assumption that the electron bunch length does not change with the single-bunch current. In practice, the bunch length
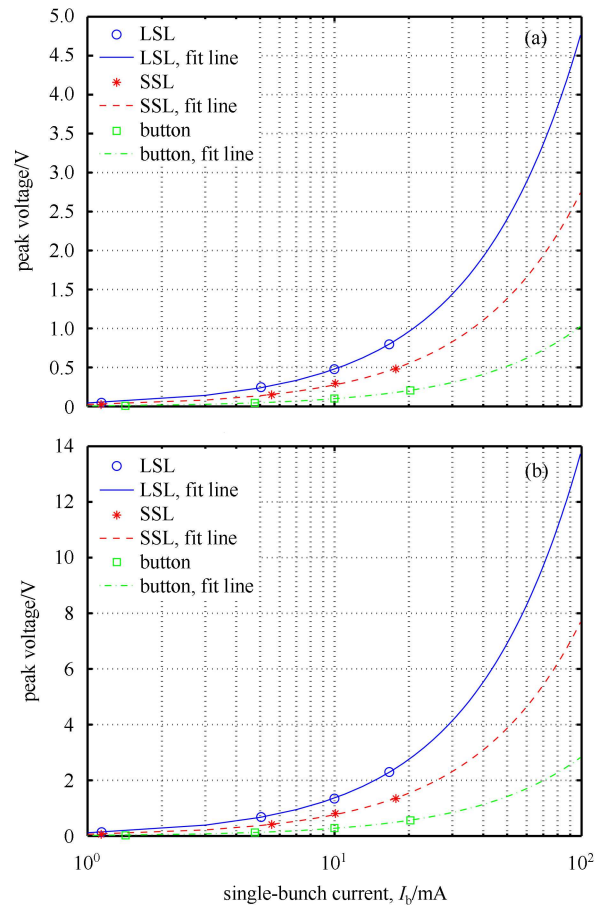


Fig. 3.   (color online) BPM pickup signal conditioning simulations using the measured time domain signal and LPFs' specifications. (a) simulation results using VLF-160 LPFs; (b) simulation results using VLF-320 LPFs. The circle, star and square symbols are the peak voltage obtained from the measured time domain signal after a 1 GHz digital LPF for the LSL, SSL and button pickups, respectively. The solid, dashed and dot-dashed lines are their fit lines.

Table 3.   Projected peak voltages of the pickup signals associated with a 100 mA single-bunch current after conditioning with LPFs.

|  | LSL/V | SSL/V | button/V |
|---|---|---|---|
| using VLF-160 LPF | 4.8 | 2.8 | 1.0 |
| using VLF-320 LPF | 13.9 | 7.8 | 2.8 |

increases with the single-bunch current due to microwave instability induced bunch lengthening. However, this effect has no significant impact on the spectral power at low frequencies, therefore, it was neglected in the simulation studies. Results in Table 3 and Fig. 3 indicate that VLF-160 LPFs can be used to effectively reduce the peak voltage at a high single-bunch current for all types of pickups, while VLF-320 LPFs are only useful for the button pickup.

### 4.4   Beam based test on signal conditioning

The signal conditioning method discussed in the previous sections is tested using the electron beam in the storage ring. A 60 feet long RG232-U cable is used to bring signals from BPM pickups to the TD7404 Tek-

tronics digital oscilloscope.   A VLF-160 or VLF-320 LPF is connected on the oscilloscope end of the cable.   This arrangement can reduce the impact of the reflected waves on the electron beam.   The measured peak voltages of the conditioned pickup signals using either VLF-160 or VLF-320 LPFs are shown in Fig. 4(a) and 4(c), respectively. Figs. 4(b) and 4(d) show the differences between the measured peak voltages and simulated values. For button and SSL pickup signals conditioned using either VLF-160 LPFs or VLF-320 LPFs, the absolute differences of the measured and calculated peak voltages are within $\pm 0.10$ V when the single-bunch current is increased from 2 mA to 25 mA. The absolute peak voltage differences of an LSL pickup are less than 0.12 V when conditioned using a VLF-16 LPF, and less than 0.45 V when conditioned using a VLF-320 LPF, in the single-bunch current range from 2 mA to 25 mA. These results indicate that the BPM electronics are expected to work properly with a single-bunch current up to 100 mA for all three types of pickups when conditioned using VLF-160 LPFs, and for button and SSL pickups when conditioned VLF-320
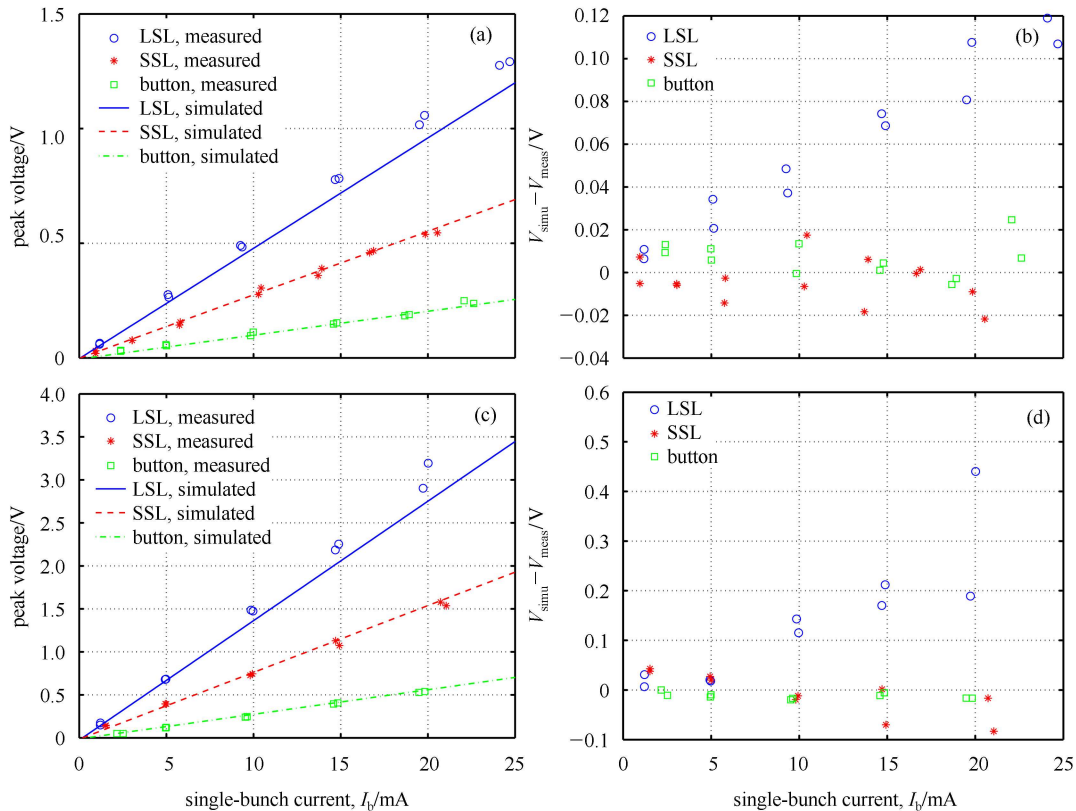


Fig. 4.   (color online) The beam based test results of the signal conditioning vs the simulated values.  (a) Peak voltages of the pickup signal conditioned using VLF-160 LPFs; (b) peak voltage differences of the beam based measurement and simulated values for VLF-160 LPFs; (c) peak voltages of the pickup signal conditioned using VLF-320 LPFs; and (d) peak voltage differences of the beam based measurement and simulated values for VLF-320 LPFs.

LPFs. The beam based measurements are consistent with the simulated results.

# 5　Beam based BPM measurement

The ultimate goal for the BPM pickup signal conditioning is to increase the BPM's dynamic range and keep the electron beam orbit stable for FEL and HIGS operations. This section reports the studies on the BPMs' performance in various operation conditions.

A set of four VLF-160 or VLF-320 LPFs are used for each BPM. These four LPFs are matched based upon careful measurements of their insertion losses in the BPM's operation range using a network analyzer. VLF-320 LPFs are only used for two button BPMs (S01 and S04) in the south straight section. For all other BPMs, VLF-160 LPFs are employed for the signal conditioning. The LPFs are installed at the BPM electronics module end to minimize the impact of the reflected signal on the electron beam.

## 5.1　Thermal effect induced orbit drifting

The measured electron beam orbit in the storage ring would drift with time if the slow global orbit feedback is turned off. This orbit drifting effect makes it difficult to study the dynamic range of the BPM system. To better understand the orbit drifting effect, a series of measurements are performed.

Many factors can contribute to the orbit drifting. One important effect is temperature related. For example, the environment temperature variation can affect the BPM readings and cause magnet movement which leads to changes of the electron beam closed orbit [22]. Table 4 shows the maximum orbit drifts measured using different types BPMs in two consecutive measurements. The global orbit feedback is turned off during the mea-

surements. In measurement #1, a single-bunch current decays from 9.0 mA to 8.1 mA in 5 minutes. In measurement #2, the bunch current decays from 4.8 mA to 4.0 mA in 11 minutes. The orbit drifts around the electron-photon collision point measured by S05QF and S07QF BPMs in these two measurements are shown in Fig. 5. The results show that the orbit drifts as a function of time, and varies tens of microns in about 10 minutes. More tests indicate that the drifting trends and amplitudes in different time windows are different.

Table 4.　Maximum orbit drift measured as a function of time using BPMs with different types of pickups. In measurement #1, the electron beam decays from 9.0 mA to 8.1 mA in 5 minutes. In measurement #2, the electron beam decays from 4.8 mA to 4.0 mA in 11 minutes.

|  | Meas. #1/μm | | Meas. #2/μm | |
|---|---|---|---|---|
|  | $\Delta x$ | $\Delta y$ | $\Delta x$ | $\Delta y$ |
| LSL | 10 | 5 | 21 | 9 |
| SSL | 21 | 5 | 44 | 10 |
| button | 12 | 11 | 26 | 24 |
| collision point | 21 | 5 | 44 | 6 |

## 5.2　Dependency on single-bunch current

According to the test results in the previous section, it is difficult to measure the actual dependency of the BPM readings on the single-bunch current because of the orbit drifting due to thermal effects. In order to reduce the orbit drifting effect, the test duration should be as short as possible. This is realized by lowering the RF voltage to about 60 kV in our tests to reduce the beam lifetime, and thus to shorten the test duration. Table 5 lists the results of two measurements for the three types of BPMs and the BPMs around the electron-photon collision point. Fig. 6 shows the orbit changes of three BPMs
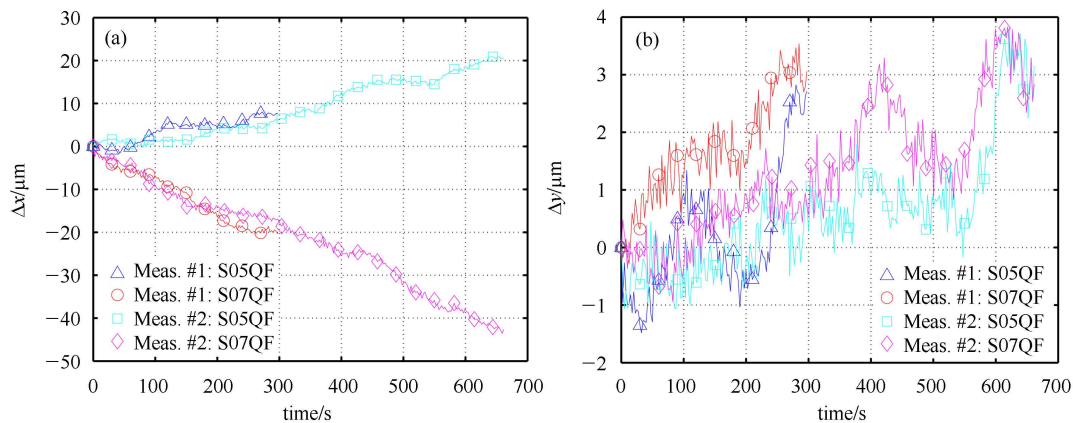


Fig. 5.　(color online) The orbit drifting around the electron-photon collision point. The global orbit feedback is turned off during the measurements. In measurement #1, the electron beam decays from 9.0 mA to 8.1 mA in 5 minutes. In measurement #2, the electron beam decays from 4.8 mA to 4.0 mA in 11 minutes. (a) The horizontal orbit; (b) the vertical orbit.
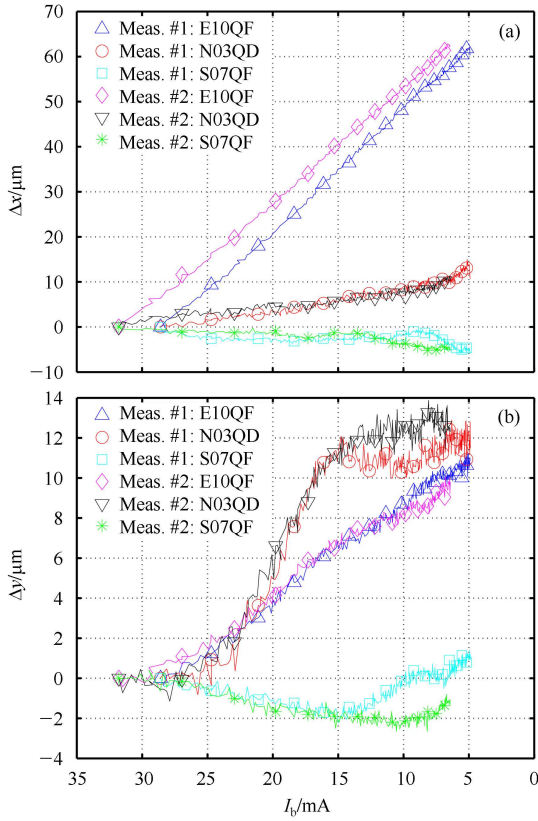
Fig. 6. (color online) Dependency of the BPM measurement on the single-bunch current. In measurement #1, a single-bunch current decays from 28.6 mA to 4.9 mA in 4.3 minutes. In measurement #2, a single-bunch current decays from 31.8 mA to 6.4 mA in 3.5 minutes. BPM E10QF, N03QD and S07QF are located in the east arc, NSS and SSS, respectively.

located in different sections as a function of the electron beam current. In the first measurement, a 28.6 mA single-bunch beam is injected into the storage ring. Then, the orbit is recorded as the beam current decays to 4.9 mA. The duration for this test is 4.3 minutes. In the second measurement, the single-bunch beam decays from 31.8 mA to 6.4 mA, and the orbit is monitored for 3.5 min. In these measurements, the horizontal readings of the arc BPMs significantly depend on the single-bunch current. This effect is attributed to the large horizontal orbit offset ($\sim$2.5 mm) in the arc BPMs necessary for using a combined quad-sextupole in the arc. The measured vertical orbit changes in the arcs have similar amplitudes as the thermal drifts in this period of time. The orbit deviation with the single-bunch current in straight sections, for both horizontal and vertical directions, also has a similar range as the thermal drifting in the same time duration. These results indicate that the dependency of the BPM readings on the single-bunch current is small

in the straight sections, and thus has little impact on the light source operation since the FELs and electron-photon collision point are all located in the SSS.

Table 5. Maximum orbit change measured as a function of the single-bunch current using BPMs with different types of pickups. In measurement #1, the electron beam decays from 28.6 mA to 4.9 mA in 4.3 minutes. The electron beam decays from 31.8 mA to 6.4 mA in 3.5 minutes in measurement #2.

|  | Meas. #1/$\mu$m | | Meas. #2/$\mu$m | |
|---|---|---|---|---|
|  | $\Delta x$ | $\Delta y$ | $\Delta x$ | $\Delta y$ |
| ARC | 116 | 14 | 127 | 15 |
| NSS | 15 | 15 | 11 | 15 |
| SSS | 33 | 25 | 25 | 15 |
| collision point | 24 | 12 | 17 | 12 |

## 5.3  Dependency on multi-bunch current

The Duke storage ring is planned to be operated in multi-bunch modes to achieve a higher $\gamma$-ray flux. To learn about the behavior of the BPMs at different multi-bunch current and in different bunch patterns, a series of studies are performed using a recently developed beam cleaning method based upon the bunch-by-bunch transverse feedback (TFB) system [23]. In each test, an electron beam with 16 evenly distributed bunches is injected into the storage ring. Then the stored bunches are killed one-by-one using the TFB system. The electron beam orbit and current are recorded before and after killing each bunch. In this test, a 100 mA, 16-bunch electron beam is evenly injected into the storage ring. The duration of this test is about 70 seconds, and the thermal effect induced orbit drift is small in this short period of time. Fig. 7 shows the measured orbit changes as a function of the beam current in one of the tests, and Fig. 8 shows the maximum orbit changes of the same measurement. The results indicate when the beam current changes from 100 mA to 80 mA, the maximum orbit variations are less than 4 $\mu$m and 8 $\mu$m in the horizontal and vertical directions, respectively. At the Compton collision point in the SSS, the typical horizontal RMS beam size is about 370 $\mu$m. With an estimated 5% emittance coupling, the typical vertical RMS beam size at the same location is about 80 $\mu$m. These BPM reading changes are less than 10% of the beam size at the collision point. As the HIGS $\gamma$-ray production is run typically with top-off injection to keep electron beam current steady, the stability of BPM readings is more than adequate for the $\gamma$-ray production in the top-off mode of operation. The result also indicates that most of the measured orbit changes are within $\pm$20 $\mu$m in both the horizontal and vertical directions when the total beam current is between 100 mA and
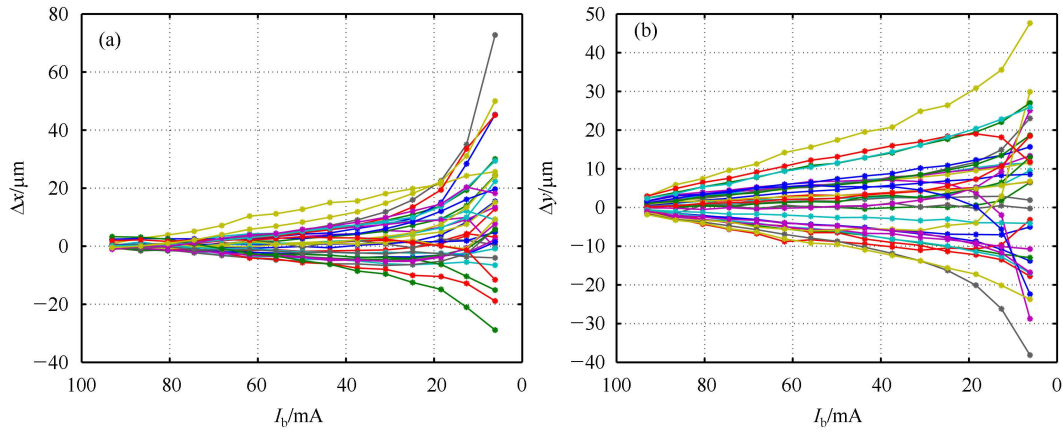
Fig. 7.    (color online) The BPM readings measured as a function of the beam current. A 100 mA electron beam with 16 evenly distributed bunches are injected in the storage ring. Then the stored bunches are killed one-by-one using the TFB system. Every line represents the BPM readings of a particular BPM. (a) Horizontal BPM readings; (b) vertical BPM readings.
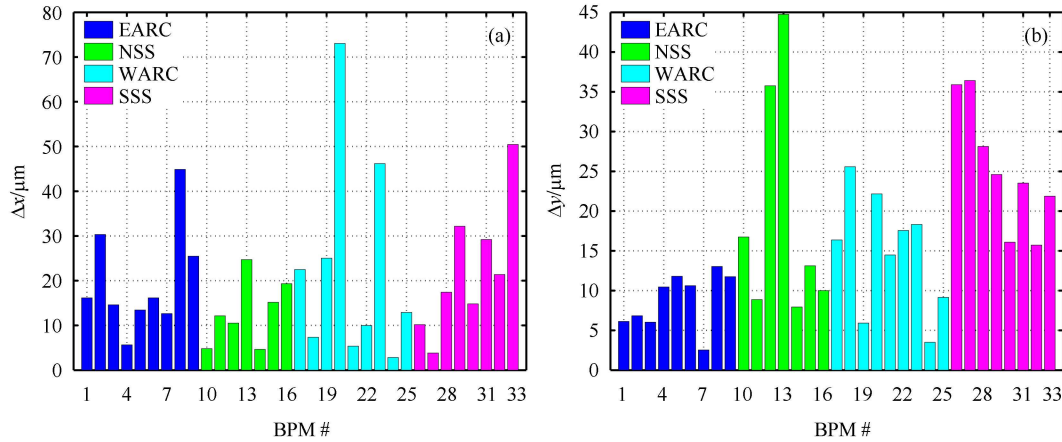


Fig. 8.    (color online) The maximum changes of the BPM readings as the beam current is reduced from 100 mA to 6 mA in the same test as shown in Fig. 7.

20 mA, and the maximum BPM reading changes are less than 50 μm in the current range from 100 to 6 mA for the BPMs in the straight sections.

## 6    Summary

The Duke storage ring has a number of operation modes with the single-bunch current varying from about 1 mA to 100 mA. To obtain precise orbit measurements in a wide range of the single-bunch current, a method for conditioning the BPM pickup signal is developed to enlarge the dynamic range of the BPMs. In this method, low pass filters are employed to effectively reduce the peak voltage of the pickup signals, and make the BPM system capable of providing reasonable orbit measurements with a single-bunch current of 1 to 100 mA.

A number of tests under different operation condi-

tions are performed to check the performance of the BPM system with signal conditioning. The dependency of the straight section BPM readings on the single-bunch current is small, and cannot be precisely measured due to thermal effects. The arc BPMs show larger orbit reading variations as the single-bunch current is changed. But this has little impact on most operations of the HIGS and FELs. The dependency of the BPM readings on the multi-bunch current and bunch pattern is also tested. The results indicate that multi-bunch current and bunch pattern do not significantly impact the BPM readings as long as the bunches are evenly filled and the total current is kept in a reasonable range (20%–30%).

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