Chinese Physics C Vol. 37, No. 7 (2013) 077006

A betatron tune measurement system based on bunch-by-bunch transverse feedback at the Duke storage ring*

XU Wei(徐卫)[1,2;1)] W. Z. Wu[2] LI Jing-Yi(李京祎)[1,2] HE Duo-Hui(何多慧)[1] Y. K. Wu[2;2)]

[1] National Synchrotron Radiation Laboratory (NSRL), University of Science and Technology of China, Hefei 230029, China
[2] FEL Laboratory, TUNL and Department of Physics, Duke University, Durham, NC 27708-0319, USA

Abstract: To combat electron beam instabilities, a digital bunch-by-bunch transverse feedback (TFB) system has been developed for the Duke storage ring. While it is capable of suppressing transverse beam instabilities for multibunch operation, the TFB system has not been needed for typical operation of the Duke storage ring. To explore the great potential of this system, we have developed beam diagnostic techniques using the TFB, in particular, the TFB based tune measurement techniques. The tune measurement technique allows us to conduct fast chromaticity measurements, compared with the existing chromaticity measurement system using a network analyzer. This new tune measurement system also enables us to measure the bunch tune for multibunch operation of the Duke storage ring. With the TFB based tune measurement system, we have studied the tune stability of the electron beam in the Duke storage ring. This tune system has also been used to calibrate the tune knob for the Duke storage ring.

Key words: transverse feedback, tune, chromaticity

PACS: 29.20.db, 29.27.Bd **DOI:** 10.1088/1674-1137/37/7/077006

1 Introduction

The light sources at the Duke accelerator facility include the storage ring based free-electron lasers (FELs) [1] and the High Intensity Gamma-ray Source (HIGS) [2]. The accelerator facility is composed of three subsystems: a 180 MeV linac pre-injector, a 0.18–1.2 GeV top-off booster injector, and a 0.25–1.2 GeV electron storage ring [3]. The betatron tunes, both vertically and horizontally, are the key parameters of an electron beam in the storage ring. Therefore, the measurement system for the betatron oscillations (betatron tunes) is one of the most important beam diagnostics. The basic approach to measure the betatron tune is to excite the electron beam and measure its response. At the Duke FEL lab, the tune measurement systems developed for both the storage ring and the booster synchrotron employ a network analyzer and an optical detector [4, 5]. This kind of optical tune measurement system works in the following way: a network analyzer generates an RF drive signal which is amplified and sent to a diagnostic stripline to excite the electron beam; the beam motion is detected using synchrotron radiation from a dipole magnet; and finally, the detected beam signal is compared with the drive signal to determine the betatron tunes.

The measurement of betatron tunes can also be realized using a bunch-by-bunch transverse feedback (TFB) system. In this paper we report our work on the development of a new tune measurement technique based on the TFB system for the Duke storage ring. We first introduce the TFB system for the Duke storage ring. Next we describe the development of the TFB based electron beam diagnostics, in particular, the TFB based tune measurement system. Using this new tune measurement system, vertical betatron tunes of a multibunch beam in the storage ring have been measured and studied. And finally we present additional applications of the TFB tune measurement system, including the study of tune stability and the calibration of the tune knob for the Duke storage ring.

2 Transverse feedback system at Duke storage ring

In order to realize high performance of a storage ring based light source, bunch-by-bunch feedback systems are employed to sustain a stable, high-current multi-bunch electron beam in the storage ring. A longitudinal feedback (LFB) system and a TFB system have been developed for the Duke storage ring. By suppressing longitu-

---

Received 9 August 2012
∗ Supported by US DOE (DE-FG02-97ER41033)
1) E-mail: wxu@ustc.edu.cn
2) E-mail: wu@fel.duke.edu

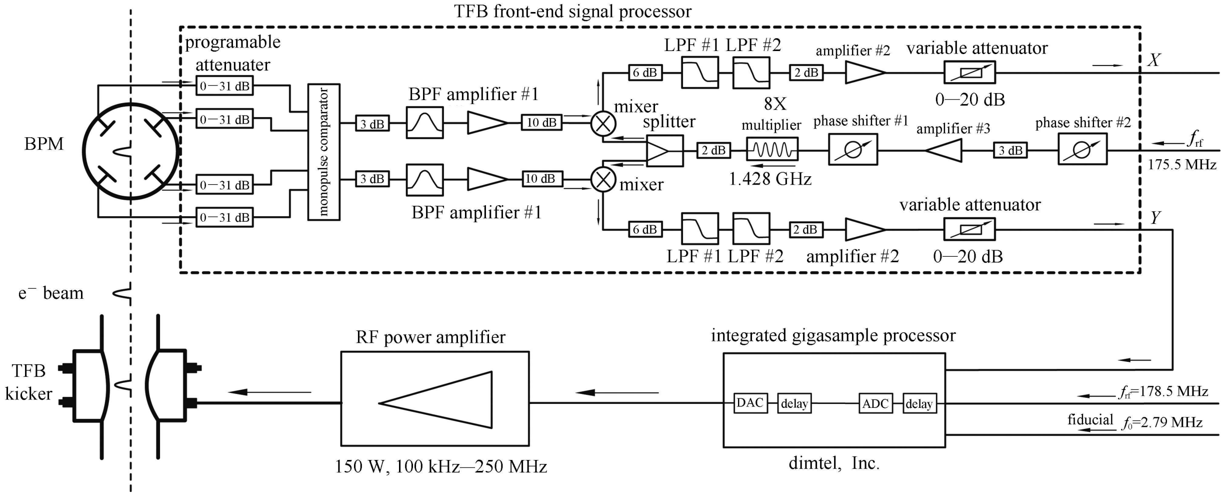

Fig. 1. The layout of the digital bunch-by-bunch transverse feedback system for the Duke storage ring. The beam signal is picked up through a button-type beam position monitor (BPM). The front-end signal processor system can detect and process both horizontal and vertical position signals of the electron beam. The TFB kicker consists of two pairs of striplines which can be used to drive the beam horizontally and vertically, respectively. Since we only have one digital processor system (iGp from Dimtel. Inc.) it is connected as a vertical feedback system to combat vertical beam instabilities which limit the maximum beam current in the Duke storage ring.

dinal coupled bunch instabilities (CBIs), the LFB system is now playing a critical role in the routine operation of the HIGS facility at Duke University [6]. The transverse feedback system was originally designed as a bunch-by-bunch, single-turn analog feedback system in collaboration with Lawrence Berkeley National Laboratory (LBNL). In order to improve its performance, we have recently upgraded the TFB system (vertically only) with an integrated Gigasample processor (iGp) which is based on a field-programmable gate array (FPGA) [7]. After tuning and optimization, the transverse feedback system is capable of suppressing the transverse beam instabilities although it is not needed for typical operation of the storage ring with either a single-bunch (for FEL operation) or a two-bunch beam (for HIGS gamma-ray production). The transverse feedback system of the Duke storage ring is schemed in Fig. 1.

A typical electron beam feedback system consists of three subsystems: (1) a signal detection system which detects the bunch signal, (2) a digital signal processing system which processes the bunch signal and produces a correction signal, and (3) an energy or momentum correction system through which the amplified correction signal is applied to the electron bunches via a feedback kicker [8]. With these features, we can develop state-of-the-art electron beam diagnostics using bunch-by-bunch feedback systems.

3 Development of TFB based beam diagnostics

It is obvious that all processes of the tune measurement system described in Section 1 can be realized using an active transverse feedback system since it can generate a signal to drive the beam and detects the corresponding beam response. Furthermore, a bunch-by-bunch transverse feedback system can drive a specific bunch and pick up its bunch response, which means that with this system we can measure the bunch tune for multibunch operation of a storage ring. This capability is not possible with the conventional tune measurement system. Using the TFB system, we have developed two different ways to measure the betatron tunes, a slow tune measurement technique and a fast tune measurement technique. We have also developed a new chromaticity measurement system which is based on the fast tune measurement technique.

3.1 Slow tune measurement technique

Using a discrete frequency scan method, we have developed a slow tune measurement technique for the Duke storage ring using the TFB system. The slow tune measurement method scans the drive frequency in a preset region while recording the beam response at each frequency. The sweep signal for excitation is generated by the iGp of the TFB system and applied to the electron beam after amplification through a transverse feedback kicker (a stripline). The RF scan signal should cover a frequency range in which the betatron tune is located. In order to get an accurate measurement result, the bandwidth of the RF drive signal should be reasonably narrow. However, a narrower bandwidth means more sweep steps, leading to a longer measurement time. Typically we set the RF drive signal bandwidth to 1 kHz. We also need to pay attention to the strength of the drive signal. If the drive signal is too weak, the beam may not be adequately excited. On the other hand, a very strong excitation may cause a tune shift due to a large beam oscillation and even beam loss. For each drive frequency, the time-domain beam signal is recorded and the fast Fourier transform (FFT) is performed to find its corresponding response in the frequency domain. Finally the drive signal and its corresponding response are put together to form a tune response diagram. In this plot, the betatron tune occurs at the frequency with the maximum beam response. Fig. 2 shows the measurement of the vertical tune of a 3.96 mA, 600 MeV single-bunch beam. Using this slow tune measurement technique, it typically takes 3 to 4 minutes to measure the tune, which is somewhat slower than the existing network analyzer based optical tune measurement system.

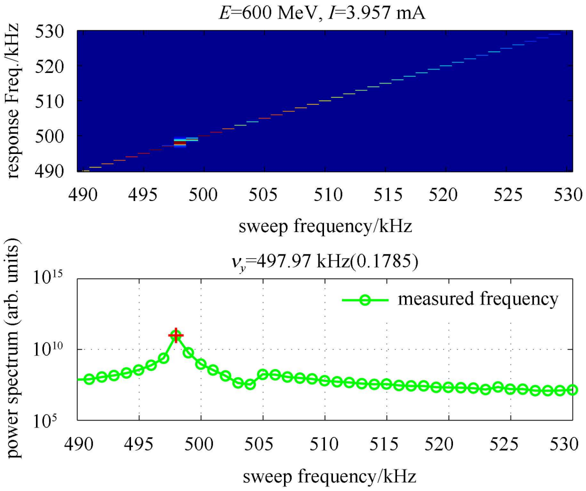

Fig. 2. A vertical tune measurement using the TFB based slow tune measurement technique. The frequency span is set to 40 kHz (490–530 kHz). The bandwidth of the sweep is set to 1 kHz, resulting in 41 sets of the beam signal data. In the lower plot, the measured beam response is shown with its peak response corresponding to the betatron signal. The measured vertical tune (a fractional tune) is $\nu_y=0.1785$ (497.97 kHz).

3.2 Fast tune measurement technique

The tune measurement technique described above is a rather slow process and a faster tune measurement technique is desirable for user operation and accelerator physics studies. A fast tune measurement system can be used to measure the betatron tune during the energy ramping of a booster synchrotron or a storage ring. In addition, a fast tune measurement system can provide us with an effective tool to study the performance of the electron beam in the storage ring with different bunch patterns and levels of current, and to study beam instabilities and impedance effects.

A much faster tune measurement technique can be developed by driving the electron beam using a broadband signal generated inside the digital processor of the TFB and subsequently recording the beam response. The FFT is then applied to the time domain beam signal to determine the beam response in the frequency domain. In order to get an accurate measurement, we need to pay attention to the FFT resolution bandwidth (RBW) of the recorded beam signal. The FFT resolution bandwidth refers to the smallest frequency that can be resolved using FFT. A smaller resolution bandwidth requires a longer acquisition period (total recording time); for a fixed sampling rate, this leads to a larger number of samples required in a measurement. Denoting this resolution as RBW, the recording time and the number of the total samples are

$$\Delta T_{\rm meas} = \frac{1}{\rm RBW}, \tag{1}$$

$$N_{\rm meas} = f_{\rm meas}\cdot\Delta T_{\rm meas} = \frac{f_{\rm meas}}{\rm RBW}, \tag{2}$$

where $f_{\rm meas}$ is the sampling rate of the acquisition system. For the Duke TFB system, its Gigasample processor can record the beam signal from all 64 buckets at the RF frequency (178 MHz) so that with one measurement, we can measure the frequency response of all 64 individual bunches. For each bunch the sampling rate is the revolution frequency of the electron beam. The beam revolution frequency in the Duke storage ring is about 2.79 MHz which is much higher than the betatron tune signals (i.e., the fractional tune signals at several hundred kHz). This ensures that the sequence of data samples can be used to reconstruct the real tune signal according to the Nyquist sampling theorem. Typically for the tune measurement a reasonable bandwidth resolution of 0.1 kHz is used. Therefore the recording time is about 10 ms. Considering the time for the system to respond and for downloading and analyzing the data, the measurement could be completed in a few seconds, which is much faster than the optical tune measurement system and the TFB based slow tune measurement technique. For a recording time of 10 ms and a sampling rate of 178 MHz (RF frequency), the total number of data taken is 2×10^6 (2^{21}), smaller than the available data buffer size of 8 MB (2^{23}) of this TFB system.

The drive signal is a modulated wideband signal with a certain bandwidth which should cover the betatron tune frequency. The sideband spacing of the modulated drive signal should be small enough in order to accurately measure the tune signal. Typically we set the sideband spacing to 50 Hz, which is smaller than the typical FFT resolution of the tune signal (0.1 kHz). Also we need to carefully set the strength of the drive. The amplitude of the drive signal should vary with the electron beam energy and current. A vertical betatron tune measurement using the TFB based fast tune measurement technique is shown in Fig. 3. As the beam signals from all 64 buckets are acquired, we can analyze them individually to obtain the bunch tune. The beam signal from bunch #1 is presented in the plot to show its bunch tune. The measured fractional vertical tune is 0.1789 which corresponds to the actual vertical tune $\nu_y = 4.1789$ (the integer part is 4).

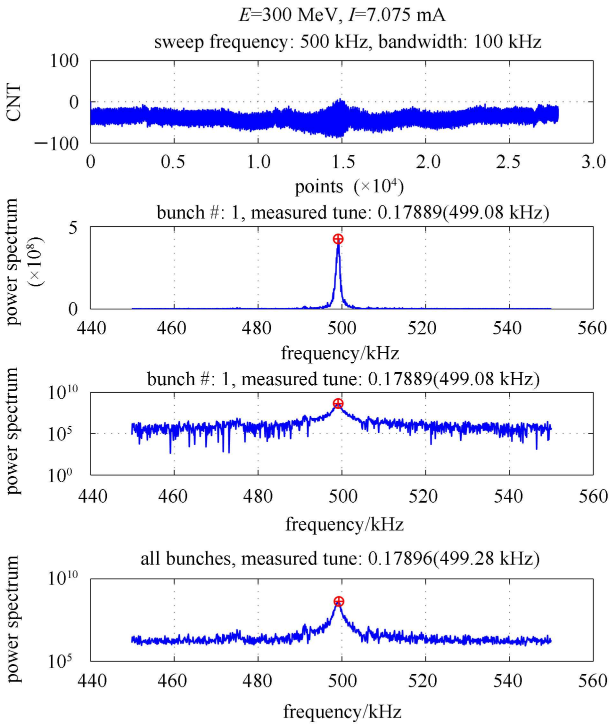

Fig. 3. A vertical tune measurement using the fast tune measurement technique. A 300 MeV, single-bunch electron beam is excited by a broadband drive signal with a bandwidth of 100 kHz (450–550 kHz). The top plot shows the overall beam signal in the time domain and the bottom plot shows the same beam signal in the frequency domain. The two plots in the middle show the power spectrum of the bunch signal from bunch #1 in the linear and logarithmic scales, respectively. The measured fractional vertical tune is ν_y=0.1789.

3.3 Chromaticity measurement system

Chromaticity is an important parameter of a storage ring which describes the variation of betatron tunes with beam energy. The chromaticity is defined as (the lowest order)

$$\xi = \frac{\mathrm{d}\nu}{\mathrm{d}(\Delta E/E)}, \tag{3}$$

where ν is the betatron tune and E is the beam energy. The definition gives us a direct way to determine the chromaticity, by measuring the tune shift with beam energy. The change of the electron beam energy can be achieved by tuning the operation frequency of the RF cavity in the storage ring:

$$\frac{\Delta E}{E} = -\alpha_{\mathrm{c}} \frac{\Delta f_{\mathrm{RF}}}{f_{\mathrm{RF}}}, \tag{4}$$

where α_{c} is the momentum compaction factor, f_{RF} is the RF frequency and Δf_{RF} is the change of the RF frequency. The momentum compaction factor for the Duke storage ring is 8.6×10^{-3}. For a typical chromaticity measurement, the range of the (relative) energy change is chosen as from −0.5% to 0.5%. In order to have a good linear fit of the measured tunes, at least five tune measurements are performed. The old chromaticity measurement system for the Duke storage ring employing a network analyzer is relatively slow. With the newly-built TFB based tune measurement system, we have developed a faster chromaticity measurement system. Fig. 4 shows the result of a typical chromaticity measurement using the TFB based tune measurement method. For this 3 mA, single-bunch beam at 600 MeV, the measured vertical chromaticity is $\xi_y = 0.171$. This measurement takes about 1 min, which is about a factor of 5 faster than the measurement using the network analyzer.

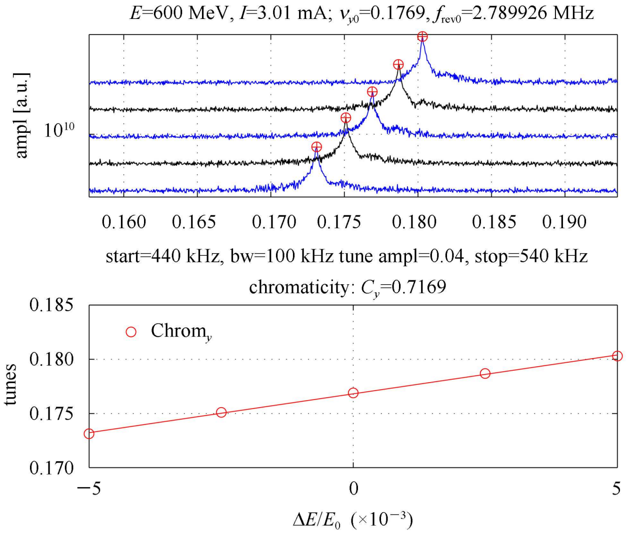

Fig. 4. A measurement of the vertical chromaticity using the TFB based tune measurement system. The upper plot shows the measured tunes for the electron beam at different energies by varying the RF frequency. The lower plot shows a linear fit to the measured tunes; the slope of the fitted line is the measured chromaticity (ξ_y=0.717).

4 Multibunch tune measurement

Multibunch operation is often adopted for a storage ring based light source to increase the total beam current, so as to obtain a high luminosity. The betatron tune of individual bunches may be different from one another. Therefore it is of great interest to measure the betatron oscillation frequencies of individual bunches rather than the overall beam tune. For example, in the process of performing bunch cleaning, to remove a particular bunch, the targeted bunch should be driven at its tune frequency precisely. This requires first performing accurate measurements of tunes of individual bunches [9].

For a stable single-bunch beam, its betatron tune can vary with beam current. The tune shift as a function of the beam current can be measured and expressed as the tune slope. The current-dependent tune shift is caused by the wakefields in the storage ring [10]. The tune shift with current measurement can be used to estimate the transverse impedance of the storage rings. Usually this type of measurement is carried out using a single-bunch beam to eliminate coupled bunch instabilities [11]. The tune shift can also be caused by the ion (or electron) clouds with multibunch operation mode in a storage ring [12]. These effects can be studied using the multibunch tune measurement system.

To demonstrate the bunch-by-bunch tune measurement capability, a multibunch tune measurement with a 2-bunch beam using the TFB based tune measurement technique is shown in Fig. 5. The tune separation of these two bunches ($\Delta\nu_y \approx 0.0038$) is mainly due to the difference of their bunch currents. We have also measured the multibunch vertical tunes of a train of 60 bunches stored in the Duke storage ring (4 continuous buckets were left empty as an ion-cleaning gap), shown in Fig. 6. The tune was measured shortly after the injection. The frequency spread of the measured bunch tunes indicates the uneven fill of electrons in 60 RF buckets. The FWHM (Lorentzian fit) tune spread of this 60-bunch beam, $\Delta\nu_y^{\mathrm{FWHM}}=0.00035$ (see Fig. 6(b)), is much larger than the typical tune spread of a single-bunch beam. In our case, the tune spread of multi-bunch beam can be attributed to two major factors: (1) the bunch-current

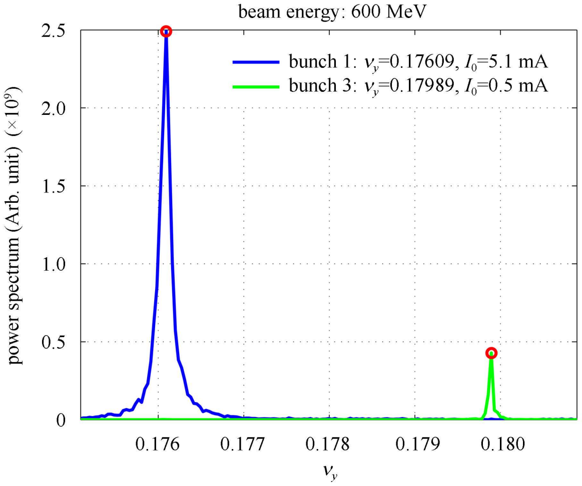

Fig. 5. A tune measurement with a 2-bunch beam (bunch #1 and bunch #3). The measured vertical tune of bunch #1 is 0.1761 with a bunch current of 5.1 mA. The measured vertical tune of bunch #3 is 0.1799 with a bunch current of 0.5 mA. The bunch tunes are measured at the same time with the same drive signal.

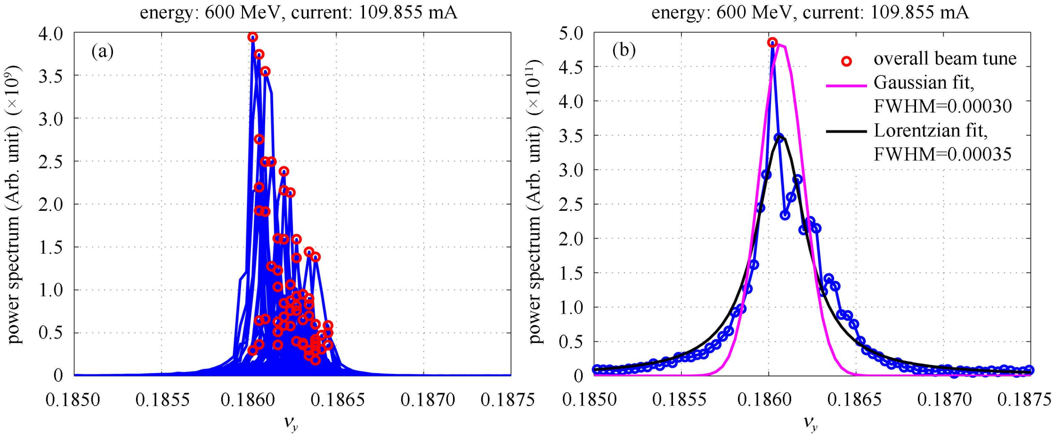

Fig. 6. A measurement of vertical tunes of 110 mA, 60-bunch electron beam at 600 MeV. (a) Measured vertical tunes of 60 individual bunches. (b) Overall vertical tune response of the beam when the time-domain beam signal from all 64 RF buckets is analyzed together. This would be the measured tune response using a tune measurement system without bunch-by-bunch capabilities. Both Gaussian fitting and Lorentzian fitting are performed. The Lorentzian curve provides a better fit especially for the foot of the tune response.

dependent tunes due to an uneven fill of electrons in various RF buckets (the effect of short-term wakefields); and (2) the coherent motion of bunches due to long-term wakefields. For the measured beam in Fig. 6, both effects are present, but the effect related to bunch-current dependent tunes is more paramount, as the beam signals from large bunches tend to have lower frequencies (Fig. 6(a)).

5 Applications

5.1 Study of tune stability at Duke storage ring

A stable tune is very important to the high performance operation of a storage ring based light source. The tune stability of a stable electron beam (without beam instabilities) is a good measure of the overall performance of magnet power supplies. For a high-performance storage ring, the power supply induced tune variations should not exceed the tune spread caused by the energy spread of the beam. For nominal operation of the Duke storage ring, the allowed maximum tune variations (RMS) are $\Delta\nu_x=0.75\times10^{-3}$ and $\Delta\nu_y=1.5\times10^{-3}$, respectively [13]. To achieve this goal, magnet power supplies with excellent stability were used and tuned to meet the tune variation requirements. The performance of individual power supplies was measured to ensure that each power supply would meet the stability specification [13].

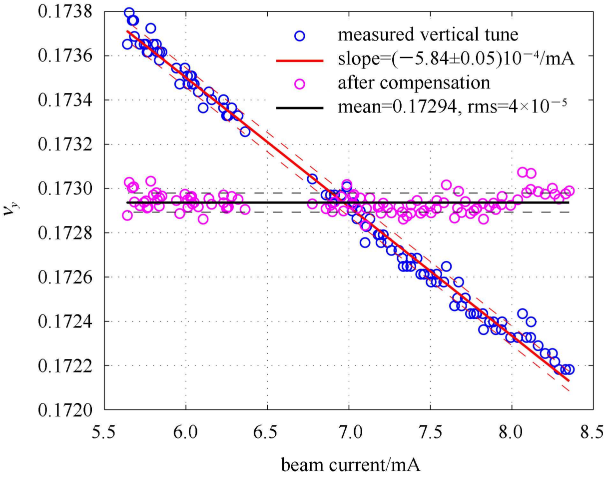

Fig. 7. The vertical tune stability measurement at the Duke storage ring. The tune is measured while a single-bunch beam current decays naturally (from 8.4 mA to 5.6 mA) at 600 MeV. The tune increases while the beam current decreases. This leads to a negative tune slope of −5.84±0.05/mA. After compensation for the effect of tune shift with current, the tune stability (RMS) is calculated as 4×10^{-5} over the measurement period of 30 min.

The vertical tune variation is investigated using the TFB based fast tune measurement system. The experiment is carried out with a single-bunch beam. The measurement results are shown in Fig. 7. After correcting the linear tune shift with current, the vertical tune variation (RMS) is only 4×10^{-5}, which is much smaller than the requirement (1.5×10^{-3}). This level of tune stability is among the best of modern storage rings, as the result of a consistent effort to improve magnet power supply stability.

5.2 Tune knob and chromaticity knob calibration

The storage ring performance can be optimized by tuning its operation point, such as tunes, chromaticities and beam orbits. At the Duke storage ring the tune knob and the chromaticity knob are important tools for operation [14]. The tune knob is implemented by adjusting the strength of a certain group of quadrupole magnets in one of the straight sections of the storage ring. The chromaticity knob is implemented by adjusting the strength of a certain group of quad-sextupole magnets in the arc sections of the storage ring. Using the TFB based tune measurement tool, we performed a calibration for the tune knob. The tune knob calibration result is shown in Fig. 8. For a tune change of $\Delta\nu_y\leqslant0.08$, the vertical tune knob is quite linear as the measured tune follows the set value of the tune knob along a straight line with a slope of 1.01. Beyond this point, the measured tune starts to deviate from the tune knob set value. The calibration indicates a finite, but rather adequate linear range of this tune knob. The chromaticity knob is also calibrated using the TFB based chromaticity measurement system. The chromaticity knob calibration is reported elsewhere [15].

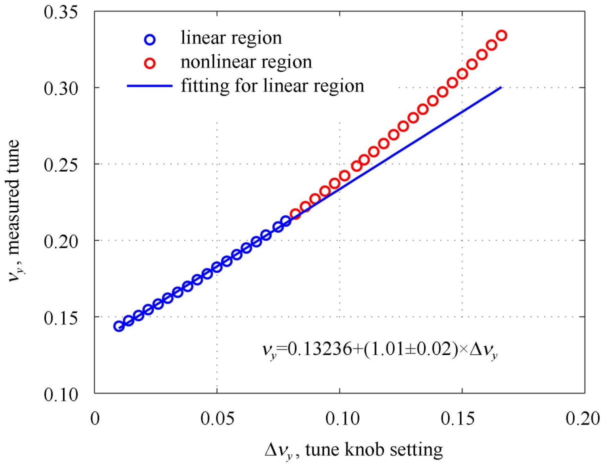

Fig. 8. The calibration of the vertical tune knob for the Duke storage ring.

6 Conclusion

The development of the TFB based electron beam diagnostics is presented in this paper. The TFB based fast tune and chromaticity measurement techniques are more efficient than the existing optical tune measurement systems using a network analyzer. Furthermore, the TFB based tune measurement system enables us to measure the betatron tune for individual bunches in the multibunch operation. With these new beam diagnostic capabilities, we have studied the tune stability and performed the calibration of the tune knob and chromaticity knob for the Duke storage ring. The TFB based tune measurement system has also been successfully used in several other research projects, including the measurement of the tune shift with the beam current for estimating the transverse impedance of the storage ring, and the study of the impedance of the vacuum chambers of FEL wigglers.

We would like to acknowledge Dr. D. Teytelman (Dimtel) for his assistance in developing the bunch-by-bunch digital TFB system for the Duke storage ring. One of the authors (W X) would also like to thank the China Scholarship Council (CSC) for supporting his visit to Duke University.

References

1 WU Y, Vinokurov N, Mikhailov S, LI J, Popov V. Physical Review Letters, 2006, **96**(22): 224801

2 Weller H, Ahmed M, GAO H, Tornow W, WU Y, GAI M, Miskimen R. Progress in Particle and Nuclear Physics, 2009, **62**(1): 257–303

3 WU Y K. Accelerator Physics Research and Light Source Development at Duke University. In Proceedings of IPAC2010, Kyoto, Japan

4 Litvinenko V, Burnham B, Hower N, Morcombe P, WU Y. Duke Storage Ring Tune Measurements System Using Razor Blade and Photomultiplier. In Proceedings of PAC1996. Dallas, Texas, USA, vol. 4. IEEE, 1995. 2461–2463

5 WU Y, LI J, Popov V, Mikhailov S, WANG P. A Tune Measurement System for Low Current and Energy Ramping Operation of a Booster Synchrotron. In Proceedings of PAC2007, Albuquerque, New Mexico, USA

6 WU W, Kim Y, LI J, Teytelman D, Busch M, WANG P, Swift G, Park I, Ko I. Nuclear Instruments & Methods in Physics Research A, 2011, **632**(1): 32–42

7 Dimtel. Inc., http://dimtel.com/

8 Oxoby G, Claus R, Fox J, Hindi H, Hoejlich J, Linscott I, Olsen J, Perbhakal S, Sapozhnikov L, Corlett J et al. Bunch-by-Bunch Longitudinal Feedback System for PEP-Ⅱ. In Proceedings of EPAC1994. Sitges, Spain

9 Weber J, Chin M, Sannibale F, Barry W. Nuclear Instruments and Methods in Physics Research Section A, 2009, **600**(2): 376–382

10 Chao A, Heifets S, Zotter B. Physical Review Special Topics-Accelerators and Beams, 2002, **5**(11): 111001

11 Zotter B. Impedances and Wakes in High-Energy Particle Accelerators. World Scientific Pub Co Inc, 1998

12 Baconnier Y. Neutralization of Accelerator Beams by Ionization of the Residual Gas. CAS-CERN Accelerator School: 2nd General Accelerator Physics, CERN, 85–19, 1985

13 WU Y, Popov V, Hartman S, Pinayev I, Mikhailov S, Morcombe P, Oakeley O, Wallace P, WANG P, Litvinenko V. Improving Power Supply Performance for the Duke Storage Ring. In Particle Accelerator Conference. 2003, vol. 2. IEEE, 2003. 752–754

14 WU Y, Litvinenko V, Burnham B, Park S, Madey J. Nuclear Science, IEEE Transactions on, 1997, **44**(5): 1753–1759

15 XU W, HE D, WU W, LI J, WU Y. Electron Beam Diagnostics Based on Transverse Feedback System at Duke Storage Ring. In Proceedings of IPAC2012, New Orleans, USA