ISBN: 978-3-95450-249-3 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2024-THBI2

# NON-DESTRUCTIVE BEAM ENERGY MEASUREMENT USING RF CAVITY BEAM ARRIVAL TIME MONITOR*

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*Abstract*

Beam energy is a key parameter for free electron laser facilities (FELs). A commonly used non-destructive system uses a beam position monitor (BPM) to measure the bunch position in a magnetic bunch compressor. At the Shanghai Soft X-ray FEL facility (SXFEL), the chicane stripline beam position method is utilized for this purpose. However, this method relies on the initial bunch position before entering the chicane and has a limited linear region. A different non-destructive beam energy system, which measures the bunch flight time using two cavity-based bunch arrival time monitors, has been proposed and tested. This paper introduces the development of this system, including design details, build-up, and measurement results. Moreover, it also covers the comparison between the two different bunch energy measurement methods from several aspects: bunch position-based and bunch flight time-based.

## INTRODUCTION

Free electron lasers (FELs) are working horses for X-ray science research all over the world for their ability to generate ultra-short and ultra-high brightness X-rays. In recent years, FELs have developed rapidly worldwide, as well as over China. Shanghai Soft X-ray FEL facility (SXFEL) and Shanghai high repetition rate XFEL and Extreme light facility (SHINE) both located at Shanghai Zhangjiang campus, are the two most representative FEL facilities in China [1-2]. Currently, SXFEL has been upgraded to a user facility and SHINE is still under construction. The development of FEL-related key technologies is important and necessary for these facilities. As one of the key parameters, beam energy measurement is also one of the important parts of FFL facilities. This is mainly due to the generation of free electron laser relies on the interaction of high energy electron bunch and seed laser in a periodic magnetic field. The radiation wavelength, $\lambda_0$, is determined by the bunch energy of the electrons, $\gamma mc^2$, and also the parameters of the undulator. Thus high-precision knowledge of the beam energy can enable higher-precision knowledge of the radiation wavelength of the generated free-electron lasers. Furthermore, the precise control of keeping the beam energy stable is of great importance for the stability of both the radiation wavelength. Therefore, a high-performance online electron bunch energy measurement system is essential. Several detection schemes of electron bunch energy have already been proposed and applied in large scale accelerators over the world. For large-scale circle accelerator facilities, such as synchrotron radiation facilities and colliders, the Compton back-scattering technique [3] and the resonant spin depolarization technique (RD) [4] are two dominant methods. For FEL facilities, a commonly used approach is measuring the horizontal bunch position between the second and third dipole magnet in a chicane, either by beam position monitor or synchrotron radiation monitor [5-7].

At SXFEL-UF, profiles are used for bunch energy measurement, but it intercepts the bunch. Therefore, a chicane stripline BPM is utilized at the LINAC 1st bunch compressor of SXFEL used for bunch energy monitoring and feedback. Besides, it has new demands from new facilities (e.g., SHINE), the bunch energy at BC1 ranges from 200 MeV to 500 MeV (as shown in Fig. 1), and a wide-range high-precision robust beam energy measurement system is required.

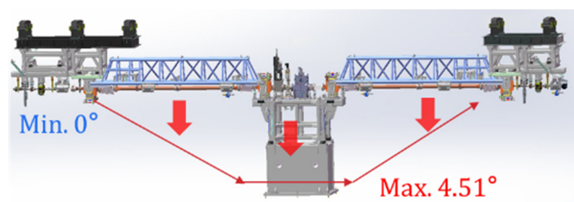


Figure 1: BC1 @ SHINE.

However, the BPM-based BEM method requires calibration of the initial position before into the chicane to obtain a more accurate beam position change, and it is limited by the SNR of the electrode signal away from the electron bunch. Instead of measuring the bunch position at Chicane, measuring the bunch flight time is another approach to knowing the energy. This has been mentioned in Ref. [5] by using EO-BAM to detect the beam flight time.

This paper is going to investigate this beam flight time-based beam energy measurement scheme, and hope to learn and compare the pros and cons of the beam flight time-based beam energy measurement method (BFT-BEM) and beam position-based beam energy measurement method (BPM-BEM).

## FUNDAMENTAL PRINCIPLES

The electron bunches with different energies have different deflection angles passing through a diode magnet. As a result, it will be dispersed into different paths. As shown in Fig. 2, the electron bunches with low energy, medium energy, and high energy travel along the $S_1, S_2$, and $S_3$ paths, respectively, and it results in a different horizontal bunch position $(x_1, x_2, x_3)$ between the second and third dipole magnet $(D_2, D_3)$. Hence the beam position monitor (BPM, purple in the figure) can be used for beam energy measurement.

* Work supported by the NSFC (Grant No. 12105346)
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Proc. 13th International Beam Instrumentation Conference,Beijing JACoW Publishing
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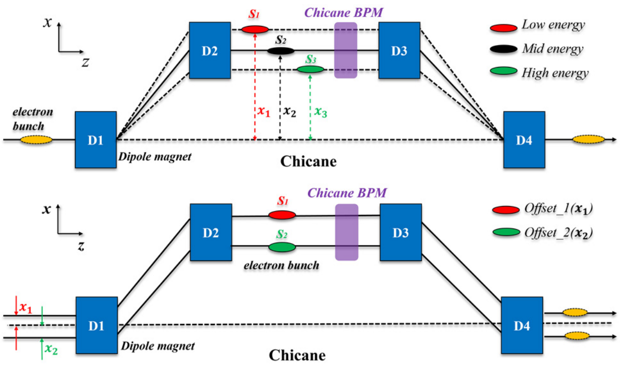


Figure 2: Schematic of electron bunch passing through a chicane.

The relation between the beam position at the chicane and the beam energy can be expressed as:

$$\Delta t = R_{56}\frac{\Delta E}{E}/\beta c, \quad (1)$$

$$t_{fly}(\gamma) = \frac{[4\rho\theta + d_0 + 2\,d_1/\cos(\theta)]}{\beta c}, \varphi = 90°. \quad (2)$$

Similarly, the relation between the bunch flight time passing through a chicane and energy can be written as:

$$\Delta x = R_{16}\frac{\Delta E}{E}. \quad (3)$$

Therefore, the key of the BT-BEM is the high-precision beam arrival/time measurement. Figure 3 shows the chicane model.

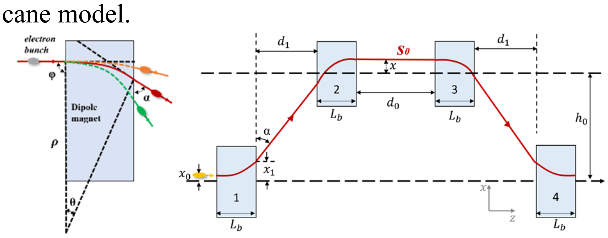


Figure 3: Model of a chicane.

Further, the parameters of the LINAC 1st chicane at SXFEL-UF are listed in Table 1.

Table 1: Chicane Specifications

| Symbol | Value | Symbol | Value |
|---|---|---|---|
| $d_0$ | 1.08 m | $L_b$ | 0.3 m |
| $d_1$ | 4.81 m | $h_0$ | 0.33 m |
| $R_{16}$ | 351mm | $R_{56}$ | 48 mm |

According to the abovementioned parameters, the relation between the beam flight time (or beam position) and the beam energy ($E = 230$ MeV) is expected to be:

$$\frac{\Delta t_{bc}}{\Delta E} = 0.696 \text{ ps/MeV}, \quad (3)$$

$$\frac{\Delta x_{bc}}{\Delta E} = 1.52 \text{ mm/MeV}. \quad (4)$$

The BFT-BEM system consists of two beam arrival time monitors to output the signals carrying the information of bunch flight time, an RF front-end electronics (RFFE) for RF signal conditioning, and a signal processor electronics for signal sampling and digital data processing. The system diagram is shown in Fig. 4.

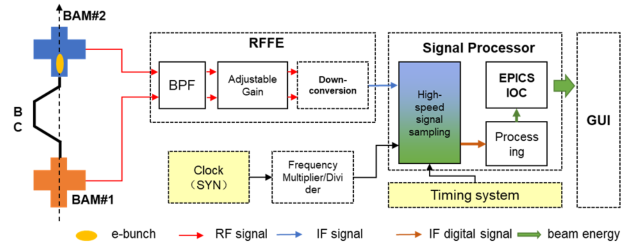


Figure 4: System diagram of BFT-BEM.

## BFT-BEM SYSTEMS

A typical RF cavity-based high-resolution beam arrival time system has been built up at SXFEL, as shown in Fig. 5. The system has been evaluated at SXFEL. The beam test results show the system resolution is better than 10 fs@100 pC, more details can be found in Ref. [8]. For convenience, a high-level graphical user interface (GUI) has been designed to calibrate and present the measured beam energy value, as shown in Fig. 6.

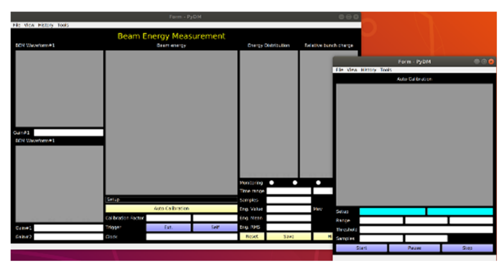


Figure 6: Beam arrival time system at SXFEL-UF.

## BEAM TEST AND ANALYSIS

To verify the relation between the beam energy and beam arrival/flight time and analyze the pros and cons of the two methods (BFT-BEM and BPM-BEM), a beam test has been designed and performed. Two BAMs (BAM01 and BAM02) and a Chicane-BPM at LINAC were used. An analytical magnet and a profile behind BAM02 were utilized, as shown in Fig. 7. Each adjusting the accelerating phase, the data of two BAMs, one SBPM, and one profile were recorded for multiple times. A total of 14 measurements were conducted.

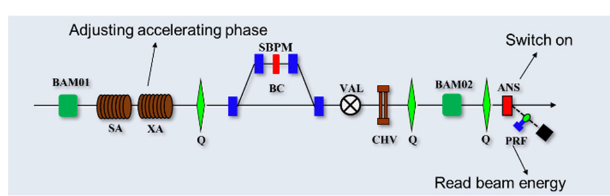


Figure 7: Layout of part LINAC of SXFEL.

The accelerating phase is gradually adjusted from -109° to -138°, the beam energy decreases from 238.53 MeV to 229.28 MeV, energy spread increases from 0.07% to 0.55%. Figure 8 shows the results of the beam energy obtained by the profiles.

Proc. 13th International Beam Instrumentation Conference,Beijing JACoW Publishing
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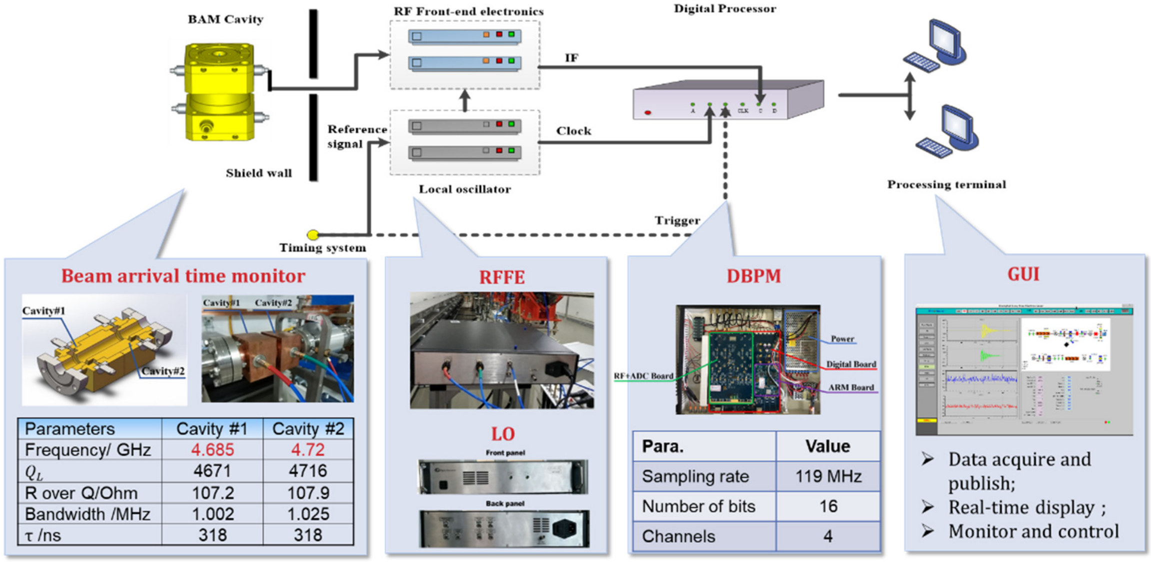


Figure 5: Beam arrival time system at SXFEL-UF.

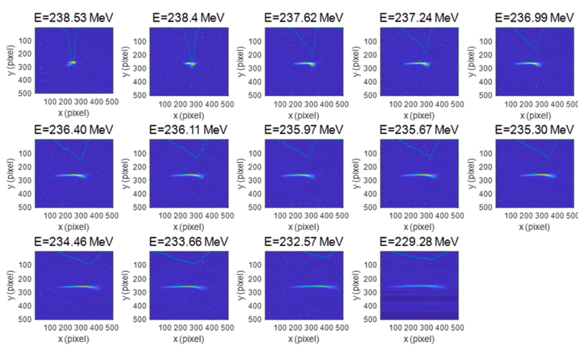


Figure 8: Bunch energies measured by profile.

Meanwhile, the bunch arrival times of over 16000 bunches were obtained. The variations of the two bunch arrival times are totally different. For BAM#1, the peak-to-peak variations are 0.35 ps, while BAM#2 has a peak-to-peak value of 6.5 ps. A linear relation between the beam energy and beam flight time is proved by the beam test. The linear factor is 0.692 ps/MeV, as presented in Fig. 9.

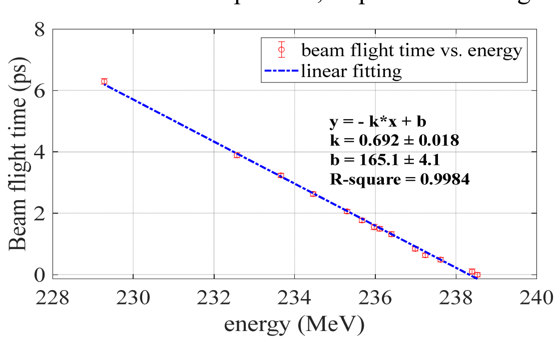


Figure 9: Bunch energies measured by profile.

In parallel, the bunch position at the chicane has also been recorded. The variation of the bunch position is shown in Fig. 10. A quadratic polynomial relation between the beam energy and beam position is obtained, as shown in Fig. 11.

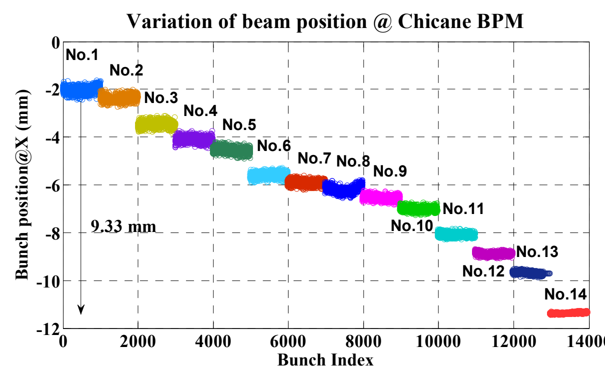


Figure 10: Variations of bunch positions.

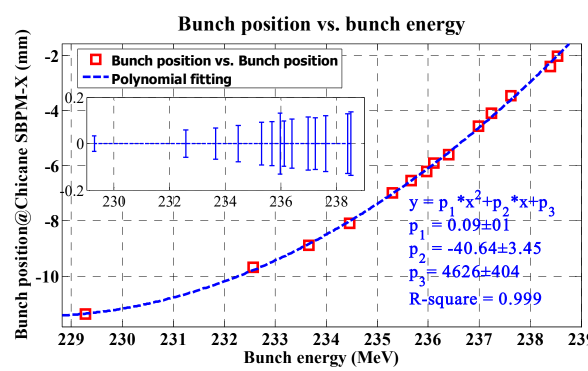


Figure 11: Correlation between bunch positions and bunch energies.

Using the calibration factors obtained by the beam test, it enables to measure the bunch energy. The average bunch energy measured by profile is 236.78 MeV, while the energy measured by BFT and BPM are 236.71 MeV and 236.89 MeV, respectively. The energy jitter measured by BFT and BPM are 5.49e-4 and 3.45e-4, respectively. Using the profile measured energy as a reference energy, the energy deviations got by BFT and BPM are 0.07 MeV and 0.11 MeV, respectively. The results are shown in Fig. 12.

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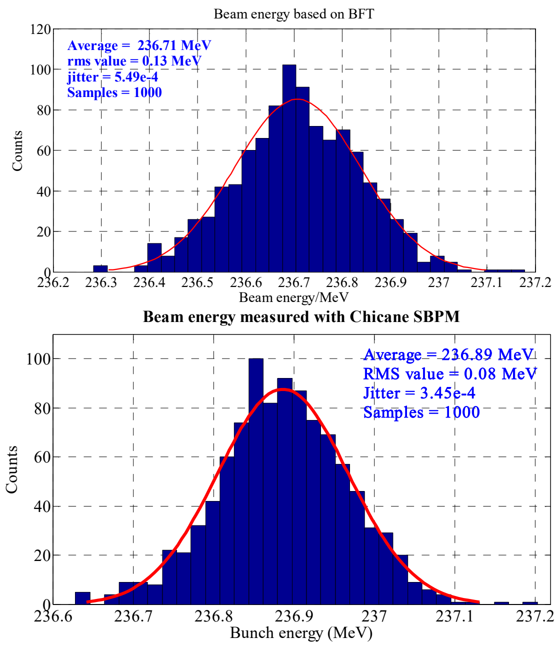


Figure 12: Bunch energies distribution measured by BFT and BPM.

## DISCUSSIOIN

Both methods can measure beam energy non-destructively based on a chicane. Both formula-based calculation and beam test results show the linear relation between the beam flight time and beam energy (230 MeV to 238 MeV). The linear factors obtained by formula-based calculation and beam test results are in very good agreement: -0.696 ps/MeV and -0.692 ps/MeV. However, the relationship between beam position and beam energy obtained from formula calculation and beam test behaves differently. The linear factor obtained by formula-based calculation is 1.52 MeV/mm, while the beam test shows they are quadratic polynomial related.

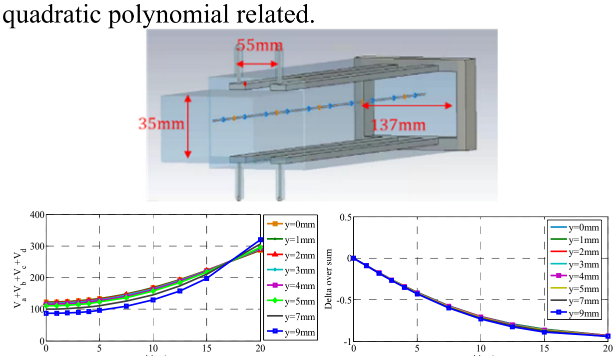


Figure 13: Model of chicane SBPM(a); The sum signal at different positions(b); The delta-over-sum at different positions(c).

This is because the chicane BPM is a rectangular four-electrode strip-line beam position monitor, as shown in Fig. 13. As the beam offset increases, the sum signal increases even the bunch charge remains constant, and the nonlinearity of delta-over-sum with bunch position becomes more obvious. The beam position change obtained using the conventional delta-over-sum algorithm is then smaller than the real beam position change. Using the non-linear algorithm, the linear factor is the beam position changes by 13.9 mm for a beam energy change of 9.25 MeV, which is almost consistent with the formula-based calculation result.

The characteristics of the two methods have been summarized in the Table 2. Overall, both have their own merits. For beam energies with only small variations (e.g., <2 MeV), the BPM-BEM is more suitable due to its higher precision. However, the bunch position needs to be calibrated or have a stabilized position before the Chicane.

For bunch energy with larger variations, the BFT-BEM method is more suitable because of its larger linear region and better accuracy.

Table 2: Summary of Results Obtained by the Two Methods

| Methods | BFT-BEM | | BPM-BEM | |
|---|---|---|---|---|
| Analytic | linear | 0.696 | linear | 1.52 |
| Beam test | linear | 0.692 | quadratic polynomial | (0.09, -40.64) |
| Range | analytic | 6.44 | analytic | 14.06 |
| | beam test | 6.34 | beam test | 13.9 |
| Energy | 236.71 | 0.07 | 236.89 | 0.11 |
| Energy jitter | 0.13 | 5.49e-4 | 0.08 | 3.45e-4 |

## CONCLUSION

The beam flight time-based and position-based beam energy measurement schemes have been investigated through formula calculations and beam tests. In particular, the beam flight time (BFT)-based beam energy measurement (BEM) system was established, optimized, and tested at SXFEL-UF. A linear relationship between the beam energy and the beam flight time through a magnetic chicane has been verified through both formula calculations and beam tests. The linear factors are essentially identical. Compared to the beam position-based beam energy measurement, this method offers a better linear range and higher accuracy. Overall, the cavity-based BFT system has the capacity for wide-range beam energy measurement.

## ACKNOWLEDGEMENTS

We would like to acknowledge the support of colleagues in our department. Especially, we would like to extend our appreciation to the engineers at SXFEL-UF for their assistance in completing the tests.

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