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STABILITY STUDY OF BEAM POSITION MEASUREMENT BASED ON HIGHER ORDER MODE SIGNALS AT FLASH

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Abstract

FLASH is a free-electron laser driven by a superconducting linac at DESY in Hamburg. It generates high-brilliance XUV and soft X-ray pulses by SASE (Self Amplified Spontaneous Emission). Many accelerating cavities are equipped with HOMBPMs (Higher Order Mode based Beam Position Monitors) to align the beam and monitor the transverse beam position. However, these lose their position prediction ability over time. In this paper, we applied an efficient measurement and signal analysis with various data process methods including PLS (Partial Least Square) and SVD (Singular Value Decomposition) to determine the transverse beam position. By fitting the HOM signals with a genetic algorithm, we implemented a new HOMBPM calibration procedure and obtained reliable beam prediction positions over a long time. A stable RMS error of about 0.2 mm by using the spectra of signals and 0.15 mm by using the new method over two months has been observed.

INTRODUCTION

FLASH [1] was originally a test facility for various physics studies of the superconducting technologies. It serves nowadays as a Free Electron Laser (FEL) user facility as well as a test facility for advanced Linac facilities such as the European XFEL and ILC. Figure 1 shows the schematic layout of FLASH with three beam lines. FLASH1, FLASH2 are used for generation of high brilliance ultra-short ultraviolet (XUV) and soft X-ray pulses. They are able to provide a beam for two experiments simultaneously. The third beamline accommodates FLASH-Forward, a beam-driven plasma-wakefield experiment. There are seven accelerating cryo-modules along the linac. Each module contains eight TESLA superconducting cavities with 1.3 GHz working frequency. There is also one module with four 3.9 GHz cavities to linearize the energy chirp induced by the first accelerating module in the longitudinal phase space.

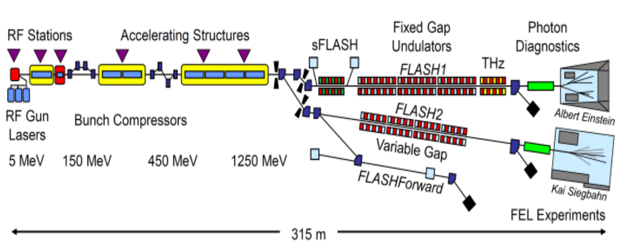

Figure 1: Schematic layout of FLASH [1].

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When an electron beam passes through the cavities, it excites wakefields, which can deteriorate the beam quality and may result in a beam-break-up instability in the worst case [2]. Therefore two couplers installed at both sides of the TESLA cavity are specially designed to extract them (see Fig. 2). The wakefields can be expanded as a multipole series of so-called modes. The modes with higher frequency than the accelerating mode are named Higher Order Modes (HOMs). Among these, dipole modes can be utilised to determine the beam position since their amplitude has linear dependence on the beam offset. Based on this, a HOMBPM system was built. A 4 μm resolution rms was observed in one cavity [3]. However, the beam position readout calibration is unstable over time [4]. In order to solve this problem, we use a method based on genetic algorithm (GA) to fit the beam excited signals. After that, several methods are applied to predict the beam position.

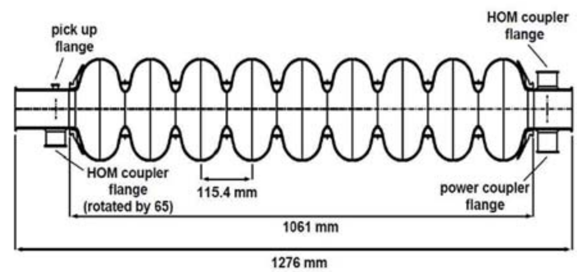

Figure 2: Drawing of the TESLA cavity with nine cells, one power input coupler, one probe antenna and two HOM couplers.

Next section introduces the measurement principle of the dipole mode signal and the GA fitting procedure. The following section presents the results of the HOMBPMs in several cavities with different calibration methods. The paper ends with conclusions.

DIPOLE MODE SIGNAL

The dipole mode signal from the HOM ports excited by a traversing bunch can be affected by four beam parameters: the bunch charge, the trajectory offset, the trajectory tilt and the bunch tilt [5]. For short bunches, as is the case at FLASH, the bunch tilt signals are vanishingly small compared with beam offset signals. A 5 mrad trajectory tilt will excite the signal with the same amplitude as 1 mm bunch offset for 1.3 GHz cavities [6]. In our measurement, the

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trajectory tilt is less than 1 mrad and therefore the contribution from the trajectory tilt to the HOM signals is very small.

Signal Measurement

Measurements have been made at the 5th cryo-module at FLASH. Figure 3 shows a sketch of the experiment [3]. The beam position was varied using two pairs of steerer magnets. The HOM signals generated when a bunch passes through the module, are measured by the electronics. The charge was read out synchronously from a nearby toroid, and the beam position from two BPMs located upstream and downstream of the module for the same bunch.

The dipole mode TE111-6 at around 1.7 GHz was selected for the HOMBPM based on the simulation results in the 1.3 GHz TESLA cavity [7]. It has strong coupling to the beam, reflected in the high R/Q parameter, and therefore it can provide higher sensitivity to the beam position. The signal is processed by a narrow band electronics. It filters the HOM signal at 1.7 GHz with a 20 MHz narrow bandpass and down mixes to 20 MHz IF (intermediate frequency), which is then sampled at about 108 MHz by an ADC. An example of a signal waveform from cavity 4 in the FLASH module 5 and its FFT spectrum are shown in Fig. 4. The dipole mode contains two close peaks, which correspond to the two polarization directions of the mode. The amplitudes of the peaks are linearly related to the beam position in the cavity.

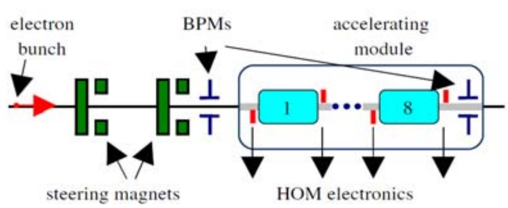

Figure 3: Setup for HOM beam position measurement.

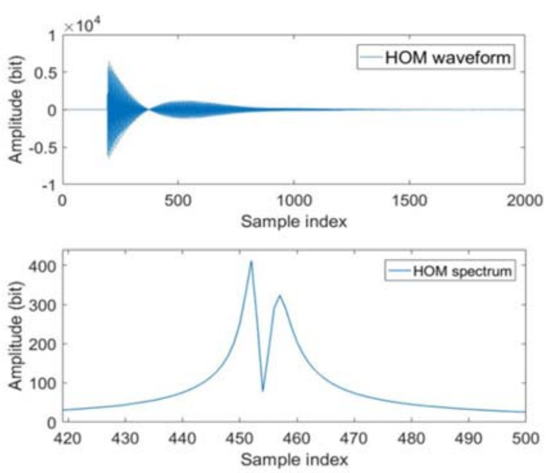

Figure 4: An example of the HOM dipole mode waveform from the HOMBPM electronics and its spectrum.

Signal Curve Fitting

As we mentioned in the first section, the HOMBPM calibration loses its reliability over days. This is mainly because of phase drifts. It proved to be difficult to reliably calculate and correct the phase drift from the waveform directly, in part because of the uncertainty in the mode frequency. Therefore we determine the phase drifts by fitting the dipole mode signal. This consists mainly of two components corresponding to the two signal peaks. Therefore the general expression of the HOM signal can be written as:

$$A = a_0 + a_1 \sin(\omega_1 t + \varphi_1) e^{-\frac{t}{\tau_1}} + a_2 \sin(\omega_2 t + \varphi_2) e^{-\frac{t}{\tau_2}}, \quad (1)$$

where a_0 is the signal offset, $a_{1,2}$ are the peak amplitudes, $\omega_{1,2}$ the angular frequencies, $\varphi_{1,2}$ the phases and $\tau_{1,2}$ the decay times of the two peaks. This function can be used to fit the signal waveform. In order to determine the parameters ($a_{1,2}$, $\varphi_{1,2}$, $\omega_{1,2}$ and $\tau_{1,2}$), we used the genetic algorithm (GA) to minimize the STD (Standard Deviation) of the difference between the measurement signal and the fitting signal.

We cut off the parts from the signal with small Signal-Noise Ratio (SNR) as well as the transient signal since these parts hardly carry any information on the beam offset. Figure 5 shows the evolution process of the STD value during the fit procedure. When the genetic iteration number is over 150, the calculation result tends to converge.

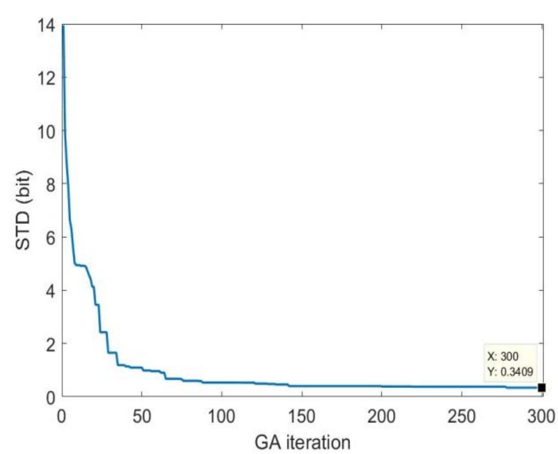

Figure 5: Iterative process of the GA.

The final STD is 0.34 bits, which is equivalent to the system noise level. The fitting curve compared with the original waveform is shown in Fig. 6. The fitting signal is basically coincident with the measured signal. The goodness of fit can be determined by the coefficient of determination (r^2), which is over 0.9990. Therefore, this method has a quite good fitting effect.

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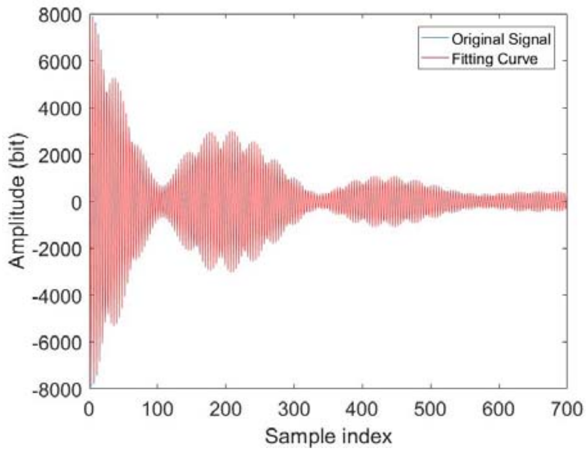

Figure 6: The original signal waveform (blue) and the fitting signal curve (red).

HOM BEAM POSITION MEASUREMENT

Data Preparation

Measurements have been implemented in the 5th cryomodule at FLASH. Data was taken on February 5th and on April 4th. In order to extract the beam position information concealed in the dipole modes signals, we construct the measurement signals in matrix form:

$$A = \begin{pmatrix} data_1 \\ data_2 \\ \vdots \\ data_m \end{pmatrix} = (a_1, a_2, \cdots a_n, 1) \in R^{m\times n}. \tag{2}$$

Matrix A represents the data for *m* measurements. It contains one additional column of ones to represent the intercept term. Both the time domain waveform and the frequency domain spectrum can be used to construct the data matrix A.

The beam position data is also put in matrix form:

$$P = \begin{pmatrix} x_1 & y_1 \\ x_2 & y_2 \\ & \vdots \\ x_m & y_m \end{pmatrix} \in R^{m\times 2}. \tag{3}$$

Matrix P represents the beam position coordinates in a given cavity interpolated from the BPM readings for all measurements.

Next we calculate the correlation between matrices A and P, to obtain the calibration matrix M:

$$A \cdot M = P. \tag{4}$$

Here the equal is used in the least square sense. For a new measurement, the beam position can be predicted by multiplying the HOM signal by the calibration matrix.

Calibration Based on PLS and SVD

Direct Linear Regression (DLR) is a straight forward method for modelling relations between sets of observed data. However, the least squares regression model is vulnerable to noise from measurement. Therefore, we apply Particle Least Square (PLS) and Singular Value Decomposition (SVD) to solve the linear system (4) to calculate the calibration matrix.

The underlying assumption of PLS is that the observed data is generated by a system driven by a small number of latent variables [8]. The PLS method can find the latent components that have high correlation with the beam position in the HOM data.

Singular Value Decomposition (SVD) is also a useful method to reduce the dimension of the system and easily find a small number of prominent components from matrix A [4]. Matrix A is decomposed into three matrices ($A = U \cdot S \cdot V^T$). The amplitudes for each signal can be constructed by:

$$A^{SVD} = A \cdot V = (A_1^{SVD}, A_2^{SVD}, \cdots A_n^{SVD}). \tag{6}$$

A_n^{SVD} is a vector that contains the amplitudes for all measurements in the n^{th} SVD mode. Normally, we select 6 ~ 10 SVD modes to construct the amplitude matrix, depending on the cavity. Figure 7 shows the calibration results of PLS and SVD using the waveforms in cavity 4 in matrix A, compared to the beam positions in the same cavity interpolated from the BPMs. Table 1 gives the corresponding RMS errors. SVD has a smaller RMS error. Therefore, we choose SVD as the conventional signal processing method.

Table 1: RMS Error of Calibration using PLS and SVD

RMS error	X	Y
PLS	0.124 mm	0.150 mm
SVD	0.118 mm	0.132 mm

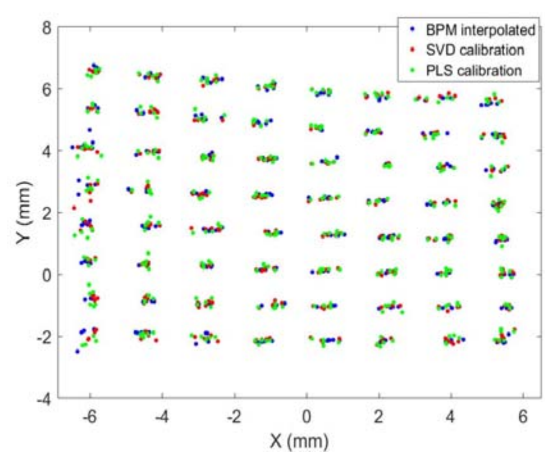

Figure 7: Calibration samples of PLS (red) and SVD (green) compared with interpolated beam positions (blue) by using the HOM waveforms.

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Long Term HOMBPM Validation

Apart from the data used for calibration, further data was measured on April 4th to validate the reliability of the HOMBPM on a short time. Also, in order to validate the long-term stability of the HOMBPM system, we applied the same calibration matrix, based on the SVD method to data taken on February 5th. For the data measured on the same date (April 4th), it is quite easily to do calibration and prediction by using the signal waveform directly. We calculated the resolution of the predicted beam position in all cavities in module 5 based on the 3-BPM method, for a small position range. The best resolution was obtained for cavity 5, 8 µm in X and 5 µm Y rms. However, there is a phase drift in the HOM time domain waveform over a long time. This leads to a mismatch of the sample amplitudes between the calibration data and the validation data. Therefore, the calibration matrix bases on waveform gives much higher RMS error. In order to solve this problem, we use the HOM spectra with SVD method.

The predicted beam positions with HOM spectra in cavity 4 are shown in Fig. 8. The RMS error is 0.22 mm in x and 0.17 mm in y in a roughly 10 mm × 10 mm scan range. The calibration and the prediction errors are basically kept on the same level over 2 months.

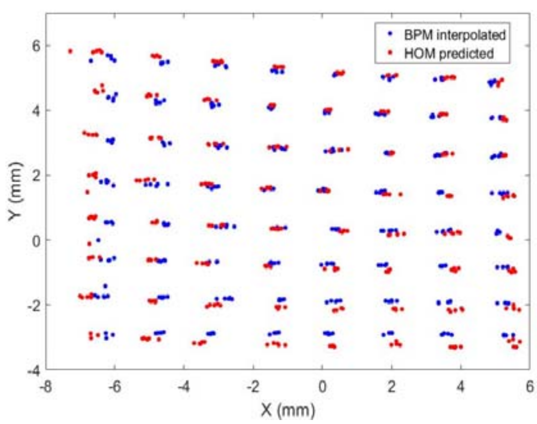

Figure 8: Predicted beam positions (red) on Feb. 5th based on HOM spectra by using SVD method compared with the BPM interpolated positions (blue).

Apart from the SVD-based methods described above, based on waveforms and on spectra, a new method of determining the beam position based on dipole signals has been developed. Based on Eq. (1), the waveform signals are reconstructed by a fitting script. The amplitudes of the two dipole mode peaks thus are obtained, which have linear dependence on the beam position. We use these amplitudes to build matrix A, and then get the calibration matrix in cavity 4 by DLR. PLS and SVD do not help here since the data is already "cleaned" by the fitting process. Afterwards, the calibration matrix is applied to the data on Feb. 5th. The results are shown in Fig. 9. This new method gives better results than the SVD/spectra method as shown in Table 2. The RMS errors remain small and comparable for the calibration and prediction samples. We plan to apply the signal fitting process to all cavities of the 5th cryo-module.

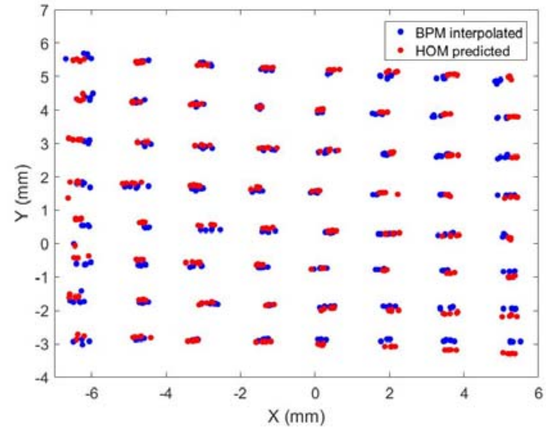

Figure 9: Predicted beam positions (red) on Feb. 5th by using the fitting method and the BPM interpolated positions (blue) as reference in cavity 4.

Table 2: RMS Error of Calibration and Prediction using Signal Fitting Method in Cavity 4

RMS error	X	Y
Calibration	0.141 mm	0.152 mm
Prediction	0.153 mm	0.137 mm

CONCLUSION

In this paper we report on a new method to stably determine the beam position over time based on HOM signals in superconducting cavities at FLASH.

When using dipole spectra, we achieved a RMS error of the beam position of about 0.2 mm over two months in the 4th cavity of 5th module. The new method gives a RMS error around 0.15 mm. The beam range was about 10 mm × 10 mm. Note that the RMS error depends on the measurement range. We remark here that this is not the resolution of the system, which is determined for a small position range. A resolution around 10 µm has been achieved in most cavities. In the future, we plan to improve the HOMBPM signal analysis method and make it work as a regular diagnostic tool at FLASH. Besides, electronics are under design for the European XFEL [9].

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