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CAVITY TILT MEASUREMENT IN A 1.3 GHz SUPERCONDUCTING CRYO-MODULE AT FLASH

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Abstract

TESLA superconducting (SC) cavities are used for the acceleration of electron bunches at FLASH. The Higher Order Modes (HOMs) excited by the beam in these cavities may cause emittance growth. The misalignment of the cavities in a cryo-module is one of the essential factors which enhance the coupling of the HOMs to the beam. The cavity offset and tilt are the two most relevant misalignments. These can be measured by help of dipole modes, based on their linear dependence on the beam offset. The cavity offset has been measured before in several modules at FLASH. However, the cavity tilt has so far proved to be difficult to be measured, because the angular dependence of the dipole mode is much weaker. By carefully targeting the beam through the middle of a cavity, the strong offset contribution to the dipole fields could be reduced. Careful data analysis based on a fitting method enabled us then to extract the information on the cavity tilt. This measurement has been implemented in the cavities in one cryo-module at FLASH. First results of the ongoing measurements from several cavities are presented in this paper. It is for the first time that the cavity tilt in several cavities has been measured.

INTRODUCTION

The Free-Electron Laser in Hamburg (FLASH) [1, 2] is a single pass free-electron laser, which generates high brilliance radiation by self-amplified spontaneous emission. The electron bunches are accelerated by the TeV-energy superconducting linear accelerator (TESLA) cavities working at 1.3 GHz. There are seven accelerating cryo-modules in the linac and each houses eight TESLA cavities.

When a bunch traverses a cavity, wakefields are excited. These fields can be decomposed into different modes, such as monopole, dipole, quadrupole, etc. modes, according to the field distribution [3]. The modes with higher frequencies than the fundamental mode used for acceleration are defined as Higher Order Modes (HOMs). These HOMs may cause emittance growth and thus reduce the beam quality. Two special couplers mounted at both ends of the TESLA cavities are used for damping the beam excited HOMs [4]. Centring the beam in the modules can also help to minimize the effect of the HOMs. Therefore, the misalignment of the cavities inside the module may enhance the coupling of the HOMs to the beam. The cavity offset and tilt are the most relevant misalignments. The dipole mode amplitude has a linear relationship with the beam offset or the beam trajectory tilt, and thus can be used for cavity misalignment measurement. The electronics [5] installed at the first five accelerating modules filter one specific dipole mode at 1.7 GHz to be used for the misalignment measurement. The cavity offset has been measured before in these modules at FLASH [6]. However, the cavity tilt has been proved to be difficult to measure because it is difficult to separate the contributions of the offset and tilt to the amplitude. Moreover, compared to the offset dependence, the angular dependence on the dipole mode is much weaker. Therefore, only results for one cavity could be obtained so far. According to this previous results, an amplitude excited by a trajectory tilt of x'_0=1 mrad corresponds to an amplitude excited by a trajectory offset of x_0=0.2 mm [7].

In order to reduce the strong offset contribution to the dipole modes, we target the beam through the center of a cavity with a small beam offset, while changing the tilt of the beam trajectory. The dipole mode signals are extracted through the HOM couplers and processed by the electronics. We have developed a signal fitting method to obtain the dipole mode amplitudes [8]. These amplitudes can be fitted as a function of the offset and tilt. Its application to several cavities in one cryo-module at FLASH is presented in this paper.

Next section introduces the measurement principle. Then we show the signal fitting method to get dipole mode amplitude. The following section presents the results of the cavity tilt measurement in several cavities. The paper ends with conclusions.

MEASUREMENT PRINCIPLES

A beam traversing a cavity in the acceleration module can excite the dipole mode in three different scenarios [6]. A beam trajectory may be parallel to the longitudinal axis with an offset of x, or pass through the cavity center with a tilt angle of x'. In addition, the bunch itself with a tilt of θ may also excite dipole modes. The corresponding amplitude of the dipole mode is proportional to [9]

$$V_x(t) \propto x \cdot e^{-(t/2\tau)} \sin(\omega t), \quad (1)$$

$$V_{x'}(t) \propto x' \cdot e^{-(t/2\tau)} \cos(\omega t), \quad (2)$$

$$V_\theta(t) \propto -\theta \cdot e^{-(t/2\tau)} \cos(\omega t), \quad (3)$$

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where ω is the angular frequency and τ is the decay time of the considered dipole mode. At FLASH, the bunch tilt does not count due to the very short length [7].

Due to the linear relationship, the amplitudes of the dipole mode excited by a beam trajectory offset and tilt can be written as $a(x - x_0)$ and $b(x' - x'_0)$, where a and b are two scaling factors between the amplitude and offset and tilt respectively, x_0 and x'_0 are the mode center and the cavity tilt. It should also be noted that these two amplitudes have a phase difference of $\pi/2$. Therefore, a sum of contributions from the beam offset and trajectory tilt is

$$A_{\text{dipole}} = \sqrt{(a(x - x_0))^2 + (b(x' - x'_0))^2}. \qquad (4)$$

In order to extract the cavity tilt information, we need to achieve a trajectory with a small offset, but a relatively large tilt with respect to the cavity.

DIPOLE MODE AMPLITUDE

Signal Measurement

Electronics installed at the first five accelerating modules are used for dipole mode signal acquisition. It filters the HOM signal at 1.7 GHz with a 20 MHz narrow bandpass and down mixes to 20 MHz IF (intermediate frequency). The signal is then sampled by ADC at a frequency of about 108 MHz [5]. Data is collected with the DOOCS control system.

A typical signal waveform measured from cavity three in the second 1.3 GHz cryo-module (ACC2) and its FFT spectrum are shown in Fig. 1. There are two peaks in the spectrum, which correspond to the two polarizations of the dipole mode. We define the polarization with lower frequency as Polarization1, and the other one as Polarization2. The frequency split of these two polarizations usually is caused by the asymmetry introduced by the couplers.

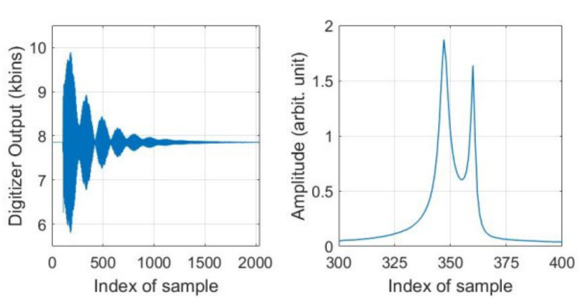

Figure 1: Waveform (left) and spectrum (right) of the dipole mode signal obtained from cavity three in ACC2.

A time window is used to cut off the transient part and the parts with small Signal Noise Ratio (SNR) in the waveform. These parts hardly carry any information on the beam. The saturation which sometimes occurs in the ADC also needs to be removed. The rest part of the waveform in the time window is shifted to zero offset and used for further analysis.

Waveform Fitting

The amplitudes obtained by the fitting method may different from the measured spectrum due to a sampling as asynchrony of the waveform in time domain. In order to reconstruct the correct amplitudes of the two polarizations from the measured spectra, we apply a method by fitting the dipole mode signal [8].

The fitting waveform is basically coincident with the original one. The difference curve between them is plotted in Fig. 2. The data is measured from cavity three in ACC2. The STD of this difference curve is about 9 bins, which is on the order of noise. The goodness of the fit can be determined by the coefficient of determination (r^2), which is over 0.99. These validate a good effect of the fitting method. The amplitudes of the two polarizations for this waveform are 2.116 kbins and 0.781 kbins.

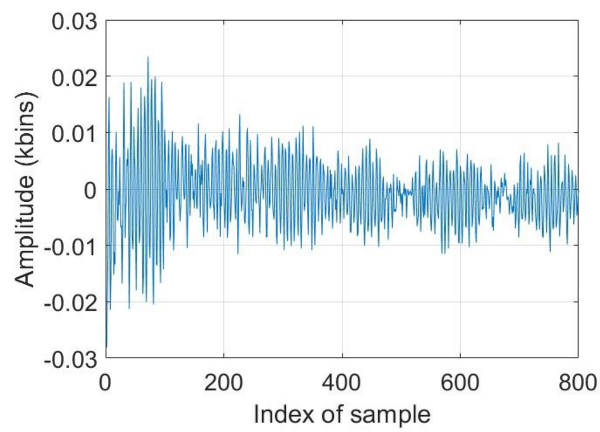

Figure 2: The difference curve between the fitting waveform and the original one.

We apply this signal fitting method to all measured data to obtain the amplitudes. Then we calibrate the relationship between the amplitude and the offset and tilt of the beam trajectory.

CAVITY TILT MEASUREMENT

Experiment Setup

We applied the cavity tilt measurement procedure in module ACC2. Figure 3 shows a schematic drawing of the experimental setup used for the cavity tilt measurement. We use two pairs of steerers to create the beam trajectories with different offset and tilt. Two BPMs located upstream and downstream of the accelerating module measure the beam positions. We switch the RF off and cycle the quadrupole magnets between the two BPMs to zero. In this case, a drift space between these two BPMs is guaranteed. Therefore, the beam position and trajectory tilt at each cavity can be interpolated from the two BPM readings. The reference cavity axis is defined by the zero readings of these two BPMs.

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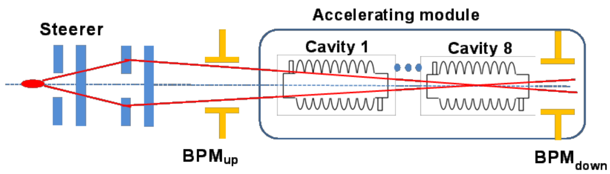

Figure 3: Schematic drawing of the experiment setup of the cavity tilt measurement.

Beam Offset Calibration

As described before, the amplitude of the dipole mode can be described as a sum of contributions from the beam offset and trajectory tilt. Normally, the beam offset contribution dominates the amplitude. At FLASH, it is much easier to make large offsets than tilt. By calibrating the beam offset, we determine the scaling factor a and the dipole mode center x_0 in Eq. (4) more accurately.

In order to do this, we use one pair of steerers to move the beam as a grid. The experimental setup is the same as we described in the HOM-based BPM calibration [8]. The beam position at the downstream BPM is in the range of 10 mm × 10 mm, while the maximum tilt is less than 0.5 mrad. Therefore, the tilt contribution is much smaller than the offset contribution and can be neglected. For a given cavity, the amplitudes of the two polarizations of the dipole mode for all trajectories and the beam positions interpolated from two BPMs are used to form two matrices respectively. The scaling factor and mode center are solved by linear regression. Figure 4 shows the beam positions interpolated from the two BPMs and the ones obtained from the dipole mode amplitudes in cavity three in ACC2. The RMS of the difference between these two kinds of beam positions is about 0.05 mm in x and 0.06 mm in y.

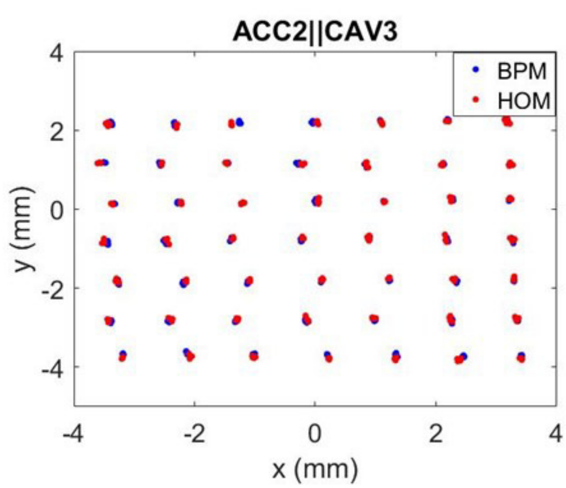

Figure 4: Calibrated beam positions (red) and the BPM interpolated positions (blue) in cavity three in ACC2.

The offset of the dipole mode center in this cavity is -0.83 mm in x and -0.80 mm in y. The scaling factors between the mode amplitude and the beam offset are 0.65 kbins/mm in x and 0.27 kbins/mm in y.

Polarization Axes

Due to the structure imperfections of the cavity and the asymmetries of the couplers, the geometrical axis of the cavity can deviate from the axis of the considered dipole mode. Furthermore, the angle between the two transverse polarization axes may deviate slightly from 90°.

According to the linear relationship between the amplitude of the polarization and the beam offset with respect to the polarization axes, it is easy to find the positions with the lowest amplitude. The polarization axes are therefore determined. These are illustrated in Fig. 5 for cavity three. The normalized amplitudes of the two polarizations are plotted as a function of beam positions in x and y respectively.

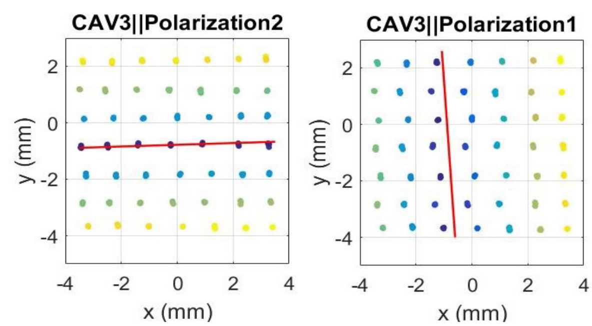

Figure 5: Normalized amplitude of Polarization2 (left) and Polarization1 (right) at cavity three in ACC2 as a function of the beam position. The red lines indicate the fitted polarization axes.

The two polarization axes form a new coordinate system $(\tilde{x}, \tilde{y})$. For cavity three, the rotation angle of the polarization axes with respect to the horizontal plane are 1.7° and 94.1° respectively. In the following analysis, the beam position and trajectory tilt are transferred into the new coordinate system.

Cavity Tilt Result

As mentioned above, the dipole mode is excited by both a beam trajectory offset and a tilt. It is hard to restore each part of the signal individually. In order to make the contribution of the tilt more prominent, we need to keep the beam trajectory close to the cavity center while varying the trajectory tilt angle.

As illustrated in Fig. 3, for each transverse plane two steerers are used. By setting a suitable constant ratio of the current of the two steerers, we can make the beam pass through the cavity center with different tilt angles. Due to the beam jitter and the error of the current ratio, it seems to be impossible to make the beam trajectory pass exactly through the cavity center. The offset is however very small. Moreover, the trajectory tilt is limited by the beamline. The angle is within ±1 mrad.

We made a linear scan in both the horizontal and vertical plane for each cavity. The data was recorded for each beam trajectory and the mode amplitudes were obtained by signal fitting. The beam positions and trajectory tilt were interpolated from the two BPMs. Then we fitted the mode amplitude with the trajectory offset and tilt based

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on Eq. (4). Figure 6 shows the normalized amplitudes of the two polarizations for the horizontal and vertical scan as a function of $(\tilde{x}, \tilde{x}')$ and $(\tilde{y}, \tilde{y}')$, respectively. And Fig. 7 shows the 3D mesh surface of the fitted amplitudes of the two polarizations. For the horizontal and vertical scans, the beam offsets are within 0.3 mm and the largest tilt is less than 1 mrad. The cavity tilt $\tilde{x}_0'$ and scaling factor b are determined by the fitting procedure. The coefficient of determination (r^2) for the fitted amplitude is over 0.95.

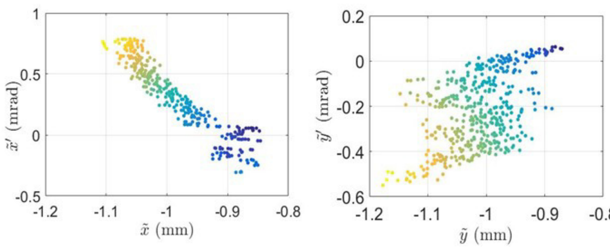

Figure 6: Normalized amplitudes of Polarization1 for the horizontal scan (left) and Polarization2 for the vertical scan (right).

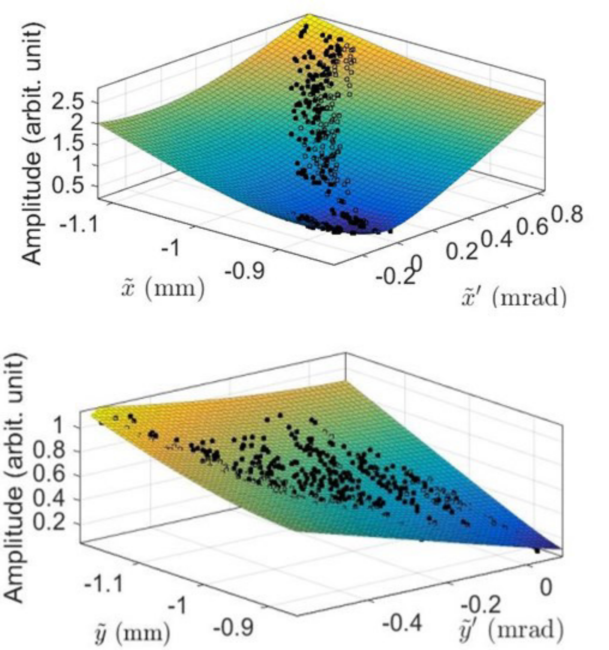

Figure 7: 3D mesh surface based on Eq. (4) by fitting the amplitudes of Polarzation1 (up) with $\tilde{x}$ and $\tilde{x}'$, Polarization2 (bottom) with $\tilde{y}$ and $\tilde{y}'$.

According to the fitting result, the cavity tilt is -0.056 mrad in $\tilde{x}$ and 0.190 mrad in $\tilde{y}$. Also, the scaling factors between the mode amplitude and the beam offset are 0.22 kbins/mrad in $\tilde{x}$ and 0.094 kbins/mard in $\tilde{y}$. Since the two scaling factors are obtained, the ratio between the offset factor and angle factor is about 1 mrad:0.34 mm for cavity three.

We also measured the cavity tilt in two other cavities in ACC2. The results are summarized in Table 1. We find similar ratios between the offset and angle dependence of the dipole mode around 1 mrad:0.3 mm for all these three cavities. This is different from the previous result as we mentioned in the first section.

Table 1: Cavity Tilt in Two Polarization Axes With Respect to the Cavity Axis

Cavity	Polarization $\tilde{x}$	Polarization $\tilde{y}$
#3	-0.056 mrad	0.190 mrad
#6	0.082 mrad	0.654 mrad
#7	0.118 mrad	0.194 mrad

CONCLUSION

Beam-excited dipole modes are used to measure the cavity tilt misalignment of the TESLA accelerating cavities inside a cryo-module at FLASH.

The mode amplitude is obtained by the waveform fitting method. We first calibrate the linear dependence between the amplitude and beam offset, and determine the two polarization axes. The two axes form a new coordinate system for data analysis.

By using two steerers to focus the beam passing through the center of a cavity, the strong offset contribution to the dipole mode amplitude could be reduced. Careful data analysis based on the fitting method enabled us then to extract the information on the cavity tilt. We measured for the first time the cavity tilt in several cavities in one module. Also, the fitting result shows a similar ratio between the tilt and offset dependence of the dipole mode amplitude of about 1 mrad:0.3 mm, which is different than measured in one cavity before.

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