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LONG TERM BEAM PHASE MONITORING BASED ON HOM SIGNALS IN SC CAVITIES AT FLASH

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Abstract

The accelerating RF fields in superconducting cavities must be controlled precisely in FEL (Free Electron Laser) facilities to avoid beam energy spread and arrival time jitter. Otherwise the beam quality is degraded. The LLRF (Low Level Radio Frequency) system controls the RF field and provides a highly stable RF reference. A new type of beam phase determination technique based on beam-excited HOMs (Higher Order Modes) in cavities has been implemented. The two special couplers installed at both ends of each cavity, pick up the signals containing both the leakage of the accelerating field and the HOM signals. Therefore the signals can be used to calculate the beam phase directly with respect to the RF phase. We analysed the factors which may affect the result of the beam phase on a long-term based on an experimental platform at FLASH. Some phase drifts between the HOM-BPhM (Beam Phase Monitor) and the LLRF system phase measurement were observed and the reason will be further studied.

INTRODUCTION

Superconducting linac based FELs (Free Electron Lasers) require control of the main RF phase relative to beam arrival time at a very precise level. At FLASH [1] and the E-XFEL (European X-ray FEL) [2], the LLRF (Low Level Radio Frequency) system is responsible for regulation of the RF fields [3]. A "vector-sum" method is applied to control the beam phase. The field vector of each single cavity is measured and then the field vector-sum of up to 32 cavities is calculated. A klystron feeds up to 4 modules with high power 1.3 GHz fields. Each module contains eight superconducting nine cell cavities. Figure 1 shows a schematic view of the LLRF control system [4]. The vector-sum has to be stabilized in amplitude and phase to a given set point. [5]. The stability of the RF amplitude and phase is required to be below 0.01% and 0.01° RMS respectively for both FLASH and the E-XFEL. The control system acts onto the vector-sum and keeps it constant, while each single cavity field within the vector-sum can fluctuate.

A new method based on HOM (Higher Order Modes) to determine the beam phase was developed [6]. When an electron bunch transverses a superconducting cavity, HOMs are excited, which carry the beam phase information. Two couplers located at each side of the TESLA cavity were specially designed to damp and extract the HOM signals. The power leakage of the accelerating field is also picked up by the HOM couplers. These fields can be used to determine the beam phase with respect to the accelerating RF fields. The monopole modes are most suited for beam phase measurement since they are not affected by beam offset. In this paper, we choose the 2nd monopole mode in TM011 band and built a scope based setup. This HOM-BPhM system is an on-line direct beam phase measurement with respect to the RF.

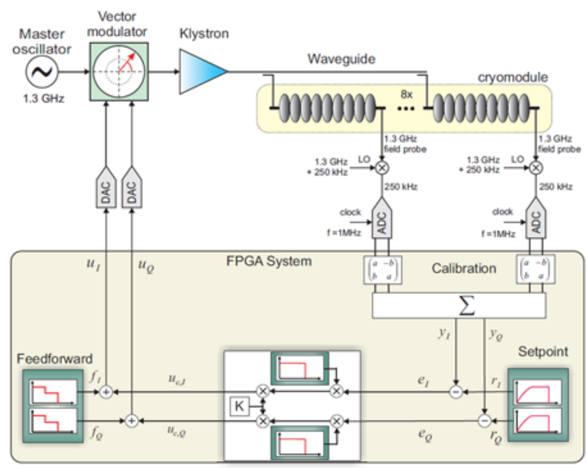

Figure 1: Schematic view of the current LLRF control system consists of analogue and digital sections [4].

In this paper, we first introduce the principle of the HOM-BPhM and then present the result of the long term measurements.

PRINCIPLE OF HOMBPHM

Beam Phase Concept

The electric field of each single cavity picked up with probe antennas give the vector-sum [7]. It is assumed that all cavities have the same physical behaviour, which means that the transient field induced by the beam has the same absolute value in each cavity [8]. The calibration is based on measuring this transient in amplitude and phase of each cavity and then calculating the ratio of the single cavity field to the vector-sum.

For maximum acceleration, the RF field should reach its maximum when the beam passes through the centre of the cavity. We define the beam phase according to the time difference between two instants: when the beam passes the cavity AND when the accelerating gradient in the cavity is maximum. The point of maximal accelerating voltage is called "on-crest", see Fig. 2 [8]. In ACC1 (the first accelerating module in FLASH), and similarly at the E-XFEL, the beam is accelerated "off-crest" to induce a bunch

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energy profile to meet the requirement for longitudinal compression in the bunch compressor section [8].

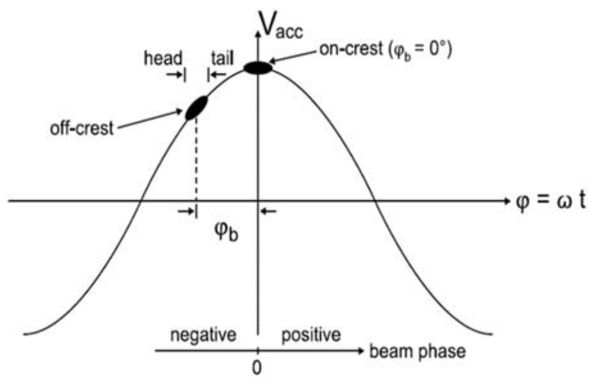

Figure 2: Schematic of beam phase, "on-crest" and "off-crest" concept [3].

The disadvantage of the vector-sum is that the single cavities are not individually controlled. The actual situation in each cavity is underdetermined.

During the facility operation, the RF field from the klystron is usually far stronger than beam excited fields, therefore the probe phase basically indicates the RF phase. It is difficult to separate the beam phase information from the probe detected signal. However, the coupler signal contains both the accelerating mode and the HOMs. This provides an approach to calculate the beam phase directly with respect to the RF phase from one measurement.

Signal Process

The 9-cell TESLA cavity contains one power input coupler, one pick-up probe antenna and two HOM couplers. The probe detects the 1.3 GHz electric field inside the cavity and the couplers at each side of the cavity provide two HOM signals (HOM1 and HOM2).

Figure 3 shows the diagram of the HOM-BPhM setup [9]. Only one channel is shown. The signal comes from the two HOM couplers on one cavity via RF cables to the measurement rack. A power splitter divides each signal in two. Each of them is then filtered individually, one centred at approximately 1.3 GHz with 100 MHz bandwidth, and the other one at approximately 2.4 GHz with 190 MHz bandwidth. Next, the two filtered signals are combined together to feed into a Tektronix oscilloscope, which has a 20 GS/s sampling rate with a 6 GHz bandwidth. One PC serves as a TCP/IP client connects the scope and the other one as a server for recording data from control system.

As we known, any periodic signal can be decomposed into a Fourier series of simple oscillating functions. In our case, the signal $x(t)$ can be written as:

$$x(t) = a_0 + \sum_{n=1}^{N} (a_n \cos(\omega_n t) + b_n \sin(\omega_n t)), \quad (1)$$

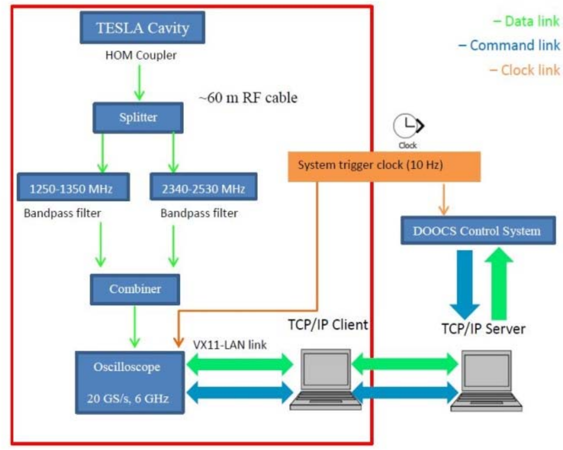

Figure 3: Block diagram of beam phase measurement setup. The figure shows one of the 2 channels from the two HOM couplers of one cavity.

where $\omega_n = 2n\pi f/N$ is the angular frequency, a_0 is the signal offset and the Fourier coefficients a_n and b_n are computed as follows:

$$\begin{aligned} a_n &= \frac{2}{T}\int_0^T x(t)\cos(\omega_n t)dt \\ b_n &= \frac{2}{T}\int_0^T x(t)\sin(\omega_n t)dt \end{aligned} \quad . \quad (2)$$

For the n^{th} HOM mode, the mode amplitude and mode phase can be calculated from its Fourier coefficients:

$$A_n = \sqrt{a_n^{\ 2} + b_n^{\ 2}}; \varphi_n = \arctan 2(a_n, b_n). \quad (3)$$

The phase of each mode can be calculated with Eq. (3). Also, according to the definition in the previous section, the beam phase with respect to the accelerating mode can be written as:

$$\varphi_{beam} = \varphi_0 - \omega_0 \cdot \sum_n \frac{w_n \varphi_n}{\omega_n}, \quad (4)$$

where φ_0 and ω_0 are the phase and angle frequency of RF at 1.3 GHz, w_n is the weight factor of mode n according to its power. However, the phase we obtained is not the correct one, due to the different phase of the signals after passing through the cables.

The spectra of the HOM signals excited by one bunch in cavity 1, ACC1, are shown in Fig. 4. The accelerating mode at 1.3 GHz from the klystron is the strongest mode, and the 8th and 9th modes among the TM011 band modes are excited stronger than the others, because of their higher *R/Q*. Therefore, these two modes are chosen to be used to determine the beam phase.

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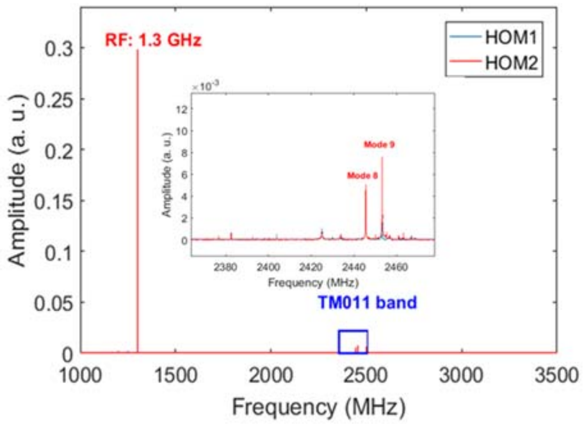

Figure 4: Measured spectra of signals HOM1 and HOM2 from the 2 couplers. Inset: spectra of TM011 mode band. The frequency step is 50 kHz.

LONG TERM HOMBPHM MONITORING

Signal Analysis

The HOM-BPhM has been used over longer periods of time to measure simultaneously the signals from the two couplers of one cavity. Figure 5 shows the beam phase obtained with different HOM modes measured from HOM1 and HOM2. The data was measured during 24 hours on August 17th. During the measurement, the RF phase was relatively stable.

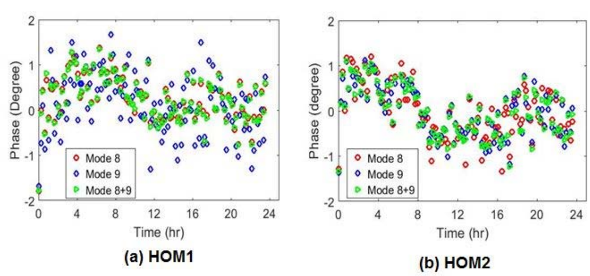

Figure 5: Beam phase measurement by using mode 8 (red), mode 9 (blue) and both modes (green) from HOM (a) and HOM2 (b).

In Fig. 4, the amplitude of mode 9 from HOM1 is smaller than of mode 8, thus it is affected more easily by noise. Also the beam phase measured with mode 9 from HOM1 has the worst RMS value in Fig. 5. The beam phase resolution calculated from coupler1 and coupler2, based on the difference of the two HOMs signals, is 0.30° for mode 8, 0.43° for mode 9 and 0.27° when using both. We obtain the best resolution by using the information of both modes.

A good knowledge of the mode frequencies is important for the phase determination (see eq. (4)). In order to investigate the effect caused by the error of the mode frequency in the phase measurement, the frequencies used for phase calculation are shifted from -50 kHz to 50 kHz with a 1 kHz step. The centre frequency measured by a Real-time Spectrum Analyser (RSA) is 2.445481 GHz for mode 8 and 2.455319 GHz for mode 9. Figure 6 shows the dependence of the phase resolution on the mode frequency shift.

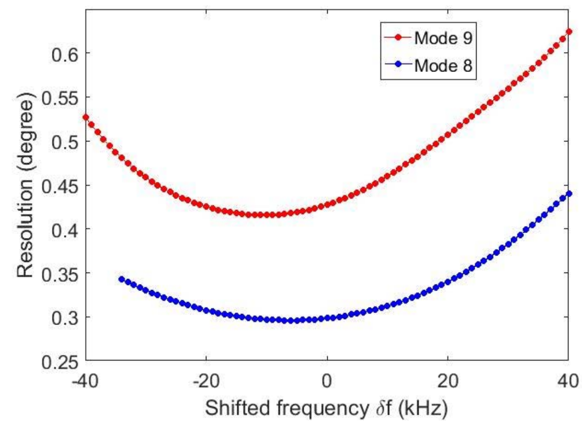

Figure 6: Resolution dependence on the frequency shift of modes 8 and 9 with a step of 1 kHz.

When the frequencies used in Eq. (4) are shifted far away from the actual mode frequencies, the resolution becomes larger. Also, the centre frequencies given by the RSA are not at the minimum resolution points. This means there is an error in the measured mode frequency. On the other hand, when the frequency error is small, the resolution is affected only slightly.

Long Term Phase Measurement

From August 1st to 21st, we measured the beam phase in cavity 1 of ACC1 at FLASH with some interruptions. Each time, the beam phase was monitored continuously for 2 to 3 days. After removing the invalid data caused by the facility commissioning, we obtained about 7500 effective measurements, shown in Fig. 7. In order to more intuitively present the relationship between the HOM phases, the probe phase and the "Vector-Sum" (VS) phase, we subtract the VS phase from the HOM phases and the probe phase, and then shifted them to zero (for the first measurements), as shown in Fig. 8. The VS calibration curve gives the value of recalibrated zero VS phase.

As we can see from the two figures, the HOM and probe phases initially have a similar evolution as the VS phase, but drift away over time. The VS calibration procedure can eliminate the phase drift and bring the RF phase in cavity one close to the VS phase. Small differences between the HOM-based measured beam phases and the probe RF phase were observed, which can be due to the beam phase jitter and non-synchronous data taking. The RMS error of the HOM-BPhM over the whole period is 0.41°. According to previous simulations [9], the resolution of the monitor depends crucially on the Signal-Noise Rate (SNR) in the system. In our system a 10 dB SNR is present, and is expected to be improved by the electronics now under design [10].

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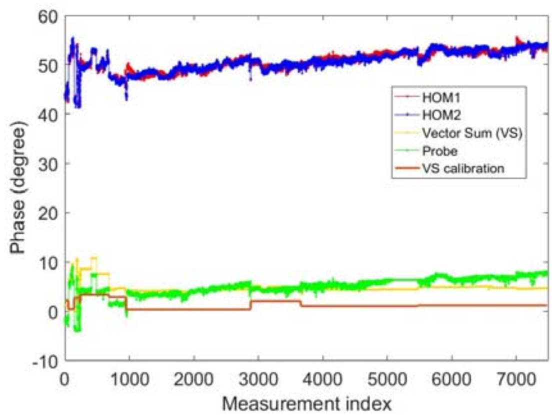

Figure 7: Long term phase measurement at FLASH. The HOM1 and HOM2 phases were measured in cavity 1 in ACC1 at FLASH with the HOM-BPhM system. The VS phase, probe phase and VS calibration phase were recorded from the control system.

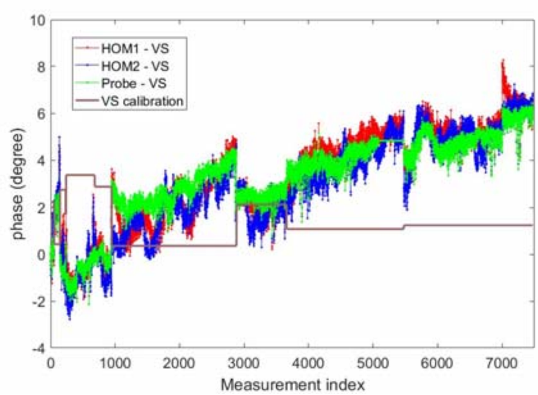

Figure 8: Phase differences of the HOM phases and probe phase with respect to the VS phase.

SUMMARY

In this paper, we present long-term HOM-based beam phase measurements in cavity 1 of the ACC1 module at FLASH. A scope based setup has been used.

The HOM phase and the probe phase are comparable. The biggest difference between the HOM phase and the probe phase is about 2°. The RMS error of the beam phase difference between HOM1 and HOM2 observed is 0.41°. This is mainly caused by the strong noise from the data acquisition system. An electronics based on direct sampling, now under development, is expected to improve the resolution.

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