MEASUREMENT OF BEAM PHASE AT FLASH USING HOMS IN ACCELERATING CAVITIES

L. Shi [†§‡*], N. Baboi [‡], R. M. Jones[†§], N. Joshi[†§],
[†]School of Physics and Astronomy, The University of Manchester, Manchester, U.K.
[§]The Cockcroft Institute of Accelerator Science and Technology, Daresbury, U.K.
[‡] Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany

Abstract

The beam phase relative to the accelerating field is of vital importance for the quality of photon beams produced in modern Free Electron Lasers based on superconducting cavities. Normally, the phase is determined by detecting the transient field induced by the beam. In this way the phase of each cavity is checked and adjusted typically every few months. In this paper, we present an on-line method of beam phase determination, based on higher order modes (HOMs) excited in the 2nd monopole band by the beam inside these cavities. A circuit model of this HOM band is also presented. Various effects on the resolution have been studied. The results indicate that the resolution is strongly dependent on the signal to noise ratio and the sampling rate. Preliminary experimental results, based on a broadband setup, reveal a resolution of ca. 0.1° RMS. These are in good agreement with simulation results. The work will pave the way for a dedicated system of beam phase monitoring, which is under development for the European XFEL which requires the beam phase to be measured to within 0.01° RMS. This will be the first implementation of a dedicated on-line beam phase monitor, based on beam-excited HOMs in accelerating cavities.

INTRODUCTION

FLASH [1][2] (Free-electron-LASer in Hamburg) is a user facility generating XUV and soft X-ray pulses by the SASE (Self Amplified Spontaneous Emission) process from energetic electron beam bunches. The layout of FLASH is schematically shown in Figure 1. One notices the two beam lines, FLASH1 and FLASH2, containing undulators where the FEL beams are produced. Seven accelerating modules, each consisting of eight TESLA superconducting cavities [3], accelerate the electron beam produced by an RF gun.

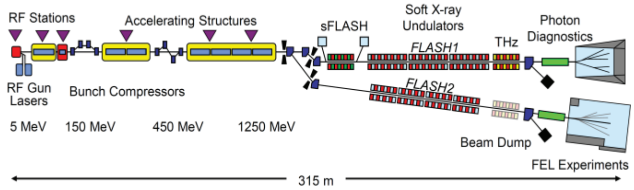

Figure 1: Layout of FLASH facility.

When a bunch of electrons transverses a superconducting cavity, wakefields are excited. These are generally detrimental to the beam if left unchecked [4]. They can be decomposed into resonant modes. For the TESLA cavity, these higher order modes (HOMs) are damped with two special couplers located on each side of the cavity. The radiation of HOMs onto the coupler ports provides us with free signals for beam diagnostic. Dipole modes can be used for beam position [5], and monopole modes for beam phase monitoring [6]. This paper focuses on beam phase measurements based on the 2nd monopole band of TESLA cavities.

The control of RF phase and amplitude are of vital importance for the acceleration of electrons. Normally the beam phase is determined by detecting the transient field induced by the beam with a field probe [7]. Here we study another method which entails monitoring the leakage of accelerating field and the damped HOMs from two HOM couplers in a cavity to obtain the beam phase. This is the only on-line direct beam phase measurement with respect to the RF.

In the first part of the paper, we present a circuit model of the 2nd monopole band. In the second part of the paper, we present beam phase measurements based on a fast scope. A comparison between simulation and measurement is made.

CIRCUIT MODEL

We apply a coupled resonant circuit model (similar to that originally developed by D. Nagle, E. Knapp and B. Knapp [8]) to facilitate the development of the HOM-based beam phase monitor. A single mode in a single cell can be represented by a resonant circuit. An N-cell cavity therefore is simulated as a circuit consisting of N coupled circuits with appropriate boundary conditions.

Coupled Circuit Model

In order to simulate the monopole band, we used the coupled parallel LC circuits described in [9]. An inductor L_n, and a capacitor C_n are connected in parallel to form the nth resonant circuit. As the cavities are superconducting, the effect of wall losses is sufficiently small that we neglect them in our circuit. The transit of the relativistic electron beam is however included in the circuit by adding a current generator I_n in parallel to each L_n C_n The coupling of cells is simulated by nearest neighbour and next nearest neighbour mutual inductances M_1 and M_2 respectively. For our 9-cell TESLA cavity we have 9 unit cells.

A dispersion curve is obtained by setting the beam current to zero and applying infinite periodic boundary conditions. In this situation all inductances are identical,

* liangliang.shi@desy.de

and $M_{1,2} = L_n \kappa_{1,2}$, where κ_1 and κ_2 are the nearest neighbour and next nearest neighbour coupling terms, respectively. This allows a relation between frequency $\omega/2\pi$ and phase ϕ to be obtained as,

$$\omega^2 = \omega_r^2(1 - \kappa_1 \cos\phi - \kappa_2 \cos 2\phi) \qquad (1)$$

where $\omega_r/2\pi$ is the resonance frequency of a single cell. For the first band, in general, nearest neighbour coupling is sufficiently accurate and hence κ_1 in this case is the fractional bandwidth of the modes [10]. However, here we add the second parameter to enhance the fitting of the HOMs. These three parameters are obtained by fitting the mode frequencies and phase advances obtained from the MAFIA simulation of a single cell subjected to infinite periodic boundary conditions [11].

Figure 2 shows a comparison between the circuit model and the MAFIA simulation results. Optimal fitting required κ_1 to be ~ -3.2% and κ_2~-0.2%. This compares to a fractional bandwidth of ~1.8% for the first band. The minus sign reflects the negative group velocity of the band and a shift in the effective coupling from inductive to capacitive [9].

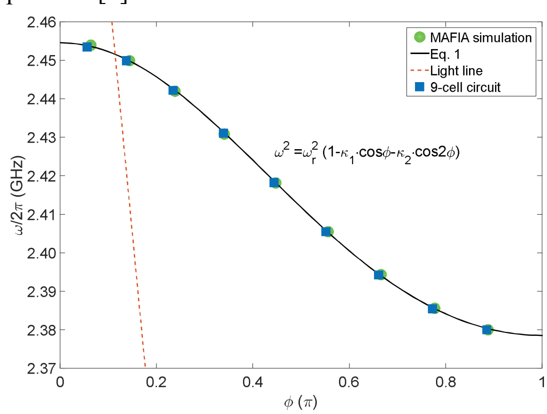

Figure 2: Dispersion curve for the 2nd monopole band.

The average discrepancy in frequency between the circuit model and the MAFIA simulation is below 0.5 MHz (0.02%).

Beam Driven Circuit Model

After the circuit model parameters are found, the current $I_n(t) = I_{n-1}(t - L/c)$ is used in each cell to simulate the propagation of the beam along the cavity. The delay is equal to half of a period of the 1.3 GHz accelerating mode. The normalized voltage across the capacitor can then be obtained by solving the circuit, as described in [9].

The coupled circuit model was implemented in Simulink® [12] and solved with a 5 ps step. The voltages across the first and ninth cells were recorded, and are denoted by HOM1 and HOM2, respectively.

The spectra of the output waveforms are shown in Figure 3. The dashed lines are the eigenmodes obtained from MAFIA. The last two modes are excited strongly. These two modes were used to determine the beam phase as described in the next section.

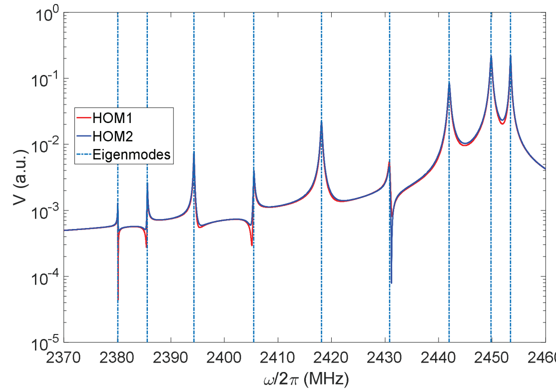

Figure 3: Spectra of voltage waveforms in the vicinity of 2.4 GHz from HOM coupler ports 1 and 2 in the circuit model. Also shown are the corresponding eigenmodes.

MEASUREMENTS OF BEAM PHASE

Setup of Beam Phase Measurements

The setup of the beam phase measurement is shown in Figure 4. The HOM signals are connected by 20 m of coaxial cable from the tunnel to the HOM patch panel.

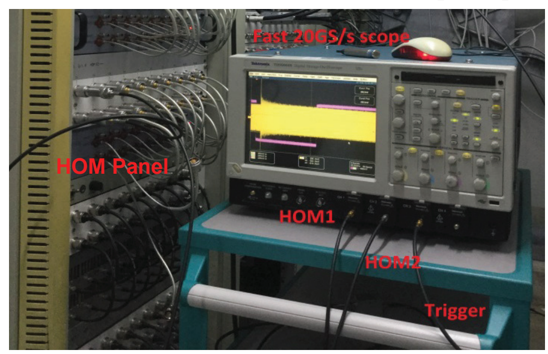

Figure 4: Setup of beam phase measurement based on a fast Tektronix scope.

The two HOM signals of a cavity were connected to a Tektronix scope (TDS6604B) with 20 GS/s, 6 GHz bandwidth. An external trigger was used to synchronize the measurement to the 10 Hz clock of the accelerator.

The spectra of waveforms measured from HOM couplers 1 and 2 are shown in Figure 5. Apart from the modes in the first monopole HOM band at approximately 2.4 GHz, there are strong leakage signals at 1.3 GHz from both couplers, which are also shown. The beam charge is approximately 0.3 nC and the accelerating gradient is approximately 18 MV/m.

The singlet monopole modes are easily identified by the overlapping spectra from HOM1 and HOM2. The last two strongly beam excited monopole modes define the beam arrival time. The phase of 1.3 GHz mode is calculated with respect to this time. The resolution is obtained by comparing the phase calculated from two channels of the same cavity.

Figure 6 shows the phase evaluated for a 5 degree step in the RF field. The resolution, based on the difference in the two HOMs signals radiated to the attached couplers, is approximately 0.1°.

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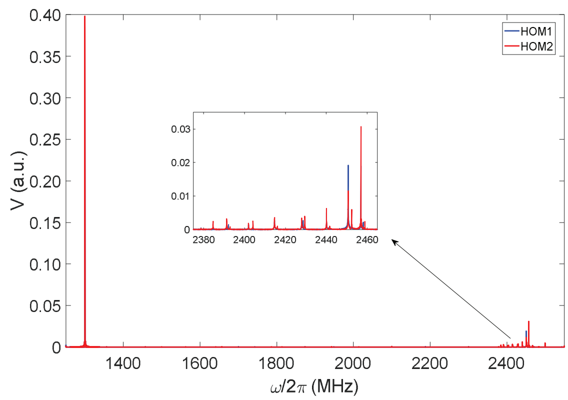

Figure 5: Measured spectra of signals from HOM couplers 1 and 2. Inset: spectra in the region of 2.4 GHz.

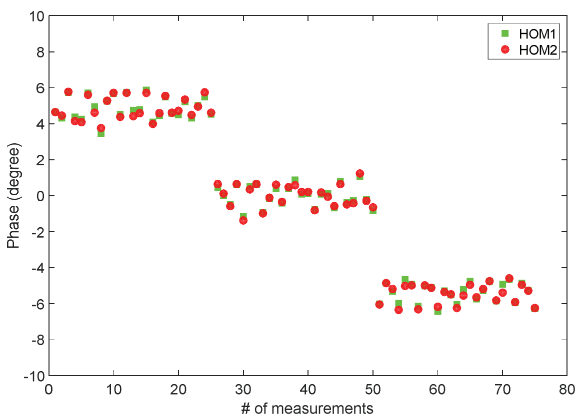

Figure 6: Beam phase based on HOMs when the RF phase is set to 5°, 0° and -5°.

Comparison with Simulation

The same method was applied to the simulation data. Firstly, a variable Gaussian white noise was added, while the sampling frequency was kept constant. Secondly, the sampling frequency was varied whilst a constant white noise level maintained. The resolution dependence on the signal to noise ratio (SNR) and the sampling frequency is shown in Figure 7.

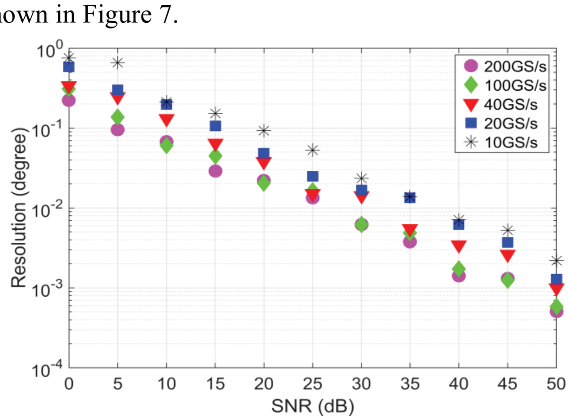

Figure 7: Circuit model applied to calculate the resolution dependence on the SNR and the sampling frequency.

The SNR from the measurements was estimated to be between 10 to 20 dB. Bearing in mind that the Tektronix scope's sampling frequency is 20 GS/s, the measured resolution agrees quite well with the circuit model. We note that the resolution can be improved by reducing the noise level and sampling at higher frequency.

SUMMARY

In this paper we presented a measurement of the beam phase based on beam-excited HOMs in accelerating cavities. In measurements, we obtained a resolution of ca. 0.1°. Based on a circuit model, we found that the resolution depends strongly on the noise level. The associated electronics for beam phase measurements based on a direct sampling technique is under development. This is a unique on-line direct measurement of beam phase with respect to the accelerating RF at FLASH. We plan to investigate means to improve the resolution for application at the European XFEL.

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