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Measurement of the beam's trajectory using the Higher Order Modes it generates in a superconducting accelerating cavity.*

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Abstract

It is well known that an electron beam excites Higher Order Modes (HOMs) as it passes through an accelerating cavity [1]. The properties of the excited signal depend not only on the cavity geometry, but on the charge and trajectory of the beam. It is, therefore, possible to use these signals as a monitor of the beam's position. Electronics were installed on all forty cavities present in the FLASH [2] linac in DESY. These electronics filter out a mode known to have a strong dependence on the beam's position, and mix this down to a frequency suitable for digitisation. An analysis technique based on Singular Value Decomposition (SVD) was developed to calculate the beam's trajectory from the output of the electronics. The entire system has been integrated into the FLASH control system.

INTRODUCTION

An electron beam moving through a superconducting accelerating cavity will produce an electromagnetic 'wake'. Short range fields produced by the head of the bunch may act on the tail, thereby degrading the quality of the beam, and longer range fields may act on subsequent bunches in a way that reduces their quality. In the worst case, these fields may be resonant with the inter-bunch spacing, causing beam blow up (BBU). This paper address the possibility of using these long range fields for diagnostic purposes.

The wake fields can be expanded as a multipole series, and, due to the cyclindrical symmetry of the accelerating cavities, each term in this series may be classified according to its azimuthal symmetry as being monopole, dipole, quadrupole, or higher order in nature. Each of these terms is known as a higher order mode (HOM).

Since HOMs are potentially damaging to the quality of the beam, their effect is reduced by careful design of the cavity geometry, and by inclusion of HOM coupler ports. There are designed as wideband devices to extract the power of the HOMs, but with a tunable bandstop filter to minimise the coupling to the accelerating mode.

Since the amplitude and phase of the HOMs are determined by the trajectory of the beam, high resolution beam position information may be calculated from an analysis of these modes. This paper describes an experiment at the FLASH facility, DESY, designed to measure the 4-dimensional transverse position of the beam (x, x', y, y') using dedicated electronics to measure a particular dipole mode. The electronics and the algorithm used to extract the position information are described, as well at the experimental technique used to calibrate the signal. The resolution of the HOM beam position monitor (HOM BPM) is measured and compared with the theoretical limit.

HIGHER ORDER MODES

The coupling of the beam to the different modes is governed by the the loss factor, $k^{(m)}$,where the integer, m, indicates the order of the mode, with $m = 0$ indicating a monopole mode, $m = 1$ dipole, etc. The loss factor is defined as follows,

$$k^{m}\left(r\right) \equiv \frac{\left|V_{L}^{(m)2}\right|}{4U^{(m)}} \tag{1}$$

The amplitude of the longitudinal field of a dipole mode, $V_L^{(1)}$, goes in proportion to r, therefore equation (1) implies that the energy coupled into the mode goes as r^2. Thus the amplitude of the measured mode will be proportional to r, as well as the bunch charge.

In the case where the beam enters the cavity above centre of a mode, and exits by the same amount below, the signal excited at the end of the cavity will tend to cancel out that generated at the beginning (due to the fact that modes with strong coupling tend to have a phase velocity very close to the velocity of the beam). There will, however, be some residual left from this 'tilt-signal' due to the angled trajectory entering and leaving the individual cells at different displacements from the mode centre. This signal may be approximated as the derivative of the offset signal, and will, therefore, have a $\frac{\pi}{2}$ phase difference from the main offset signal.

Dipole modes have two orthogonal polarisations who may or may not be degenerate in frequency. The alignment of the polarisation axis is not necessarily coincident with the laboratory x and y axis, and will be strongly affected by the position of the HOM couplers, as well as cavity imperfections.

It is, therefore possible to define four defining parameters of an individual HOM signal – the amplitude and phase of each of the two polarisations – that correlate to the four degrees of freedom of the beam's trajectory – x, x', y, and y'.

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HOM ELECTRONICS

The FLASH cavities have been simulated, and it has been calculated that there is a dipole mode at a frequency of ~1.7 GHz that couples strongly to the beam [3]. Electronics were designed to strongly bandpass filter around this frequency, downmix to a lower frequency, and digitise the output. Figure 1 shows a simple block diagram of the electronics. For more details refer to [4]. Figure 2 shows an example of a digitised pulse.

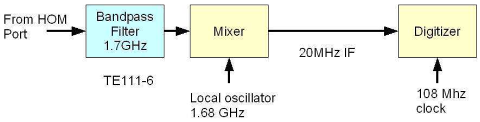

Figure 1: Block diagram of the HOM mixing electronics.

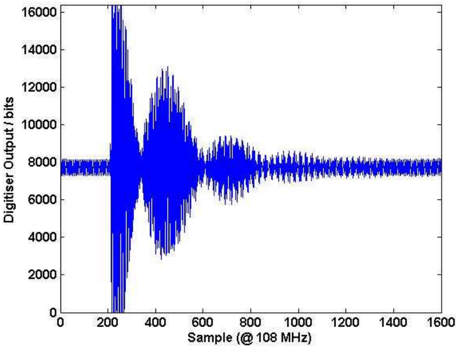

Figure 2: Example of the output of the HOM electronics for a single bunch beam.

The FLASH linac consisted of five accelerating modules, known as ACC1, ACC2, etc., each of which consisted of eight accelerating cavities. As shown in figure 3, the beam's position was controlled by two horizontal and two vertical steerers upstream of the module under investigation, and the trajectory of each pulse was interpolated from up- and down-stream BPMs.

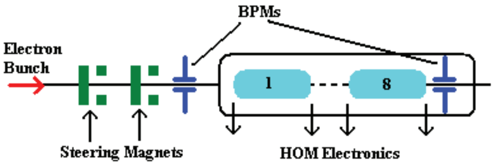

Figure 3: Cartoon of experimental setup showing two x and two y steerers upstream of a module, and the BPMs used to interpolate the position at each cavity.

CALIBRATION AND POSITION MEASUREMENT ALGORITHM

A possible analysis algorithm might involve calculating the matrix, M, that converts the amplitude, A_i, and phase, ϕ_i, of each polarisation, i (where $i = 1, 2$), to the 4D position. This requires knowledge of the different centre frequencies of each of the polarisations for each of the cavities. With the added complication that many of the modes will be almost exactly degenerate, this makes it quite difficult to find these frequencies for all forty cavities. An alternative analysis method based on singular value decomposition (SVD) was developed.

SVD was used to calculate the eigenvectors of the HOM output along with their eigenvalues. The SVD input was a $n \times j$ matrix, where n is the number of machine pulses measured ($\geq$100), and j is the number of discrete samples recorded by the digitiser for each pulse (~1500). Since one polarisation has zero coupling to one HOM port, the information from both couplers should be concatenated into one data string, as shown in figure 4. Therefore, j will be twice the length of a single digitiser output. Figure 5 shows the eight strongest basis vectors in the data set, along with their associated eigenvectors, σ.

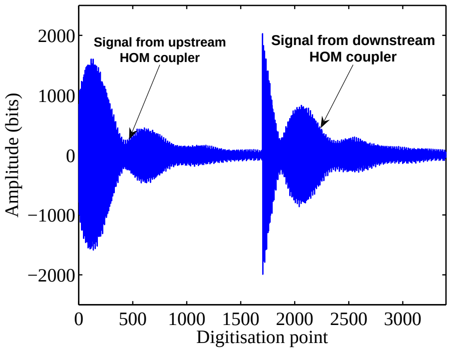

Figure 4: HOM signals from both couplers concatenated in order to build the SVD input matrix.

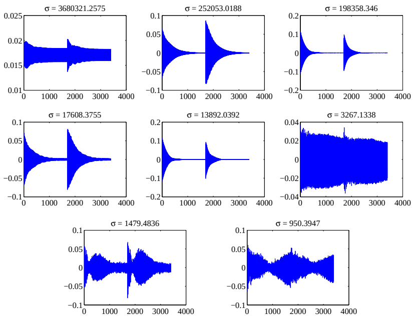

Figure 5: Orthonormal basis set calculated from SVD.

The amplitude of each of the eigenvectors may be calculated for each of the machine pulses by finding the dot product of the SVD vector with the digitiser data. The array of amplitudes is then regressed against the 4D position in order to find the conversion matrix.

RESOLUTION

To calculate the resolution, a data-set of ~250 pulses was recorded, and the position of the beam was calculated from the HOMs, using the SVD modes and conversion matrix. These measurements were compared with those interpolated from the BPMs, and the spread of the differences was found to be consistent with the resolution of the BPMs (~10 μm), implying that the HOMs provide a measurement consistent with the BPM measurement, but of a higher resolution.

In order to determine the resolution of the HOM measurement, the position measured at a cavity close to the centre of the module (for example cavity #5) was compared to the position interpolated from its neighbouring cavities (i.e. cavities #4 and #6). The spread of the differences between these is shown in figures (6), and (7) for x, x', y, and y' respectively.

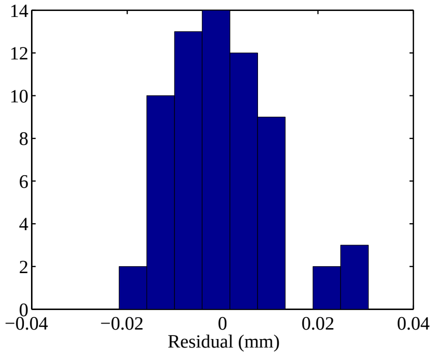

Figure 6: Resolution of the x measurement for cavity #5 in ACC5.

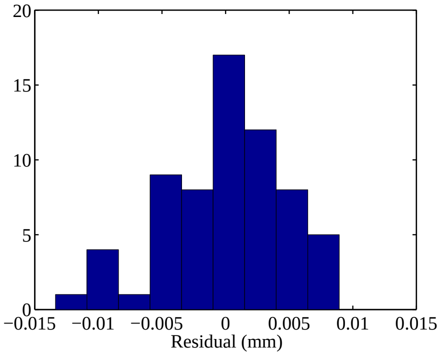

Figure 7: Resolution of the x measurement for cavity #5 in ACC5.

The resolutions, defined as the standard deviation of the spread of each of these plots, corrected by a geometric factor of $\sqrt{2}$, were calculated to be,

- x: 11 μm
- x': 175 μrad
- y: 5 μm
- y': 140 μrad

Given the coupling, $k^{(m)}$, of this mode, and the thermal noise present in the electronics, it is possible to calculate the theoretical minimum resolution of this device. Once the cable losses and the noise figure of the electronics, the minimum position resolution is ~130 nm, and the minimum angular resolution is ~1 μrad.

The cause of the large discrepancy between the theoretical and achieved resolutions is due to the noise of the toroids that perform the charge measurement, and amplitude and phase jitter of the mixer LO.

CONCLUSIONS

It has been demonstrated that strong dipole HOMs may be used to determine the postion of the beam with a resolution of ~5 μm, and that there is potential to significantly improve this resolution. The electronics for these devices have been installed onto five of the accelerating modules at FLASH, providing forty additional position measurements in the linac, and the algorithm has been integrated into the control system.

A demonstration of good multi-bunch performance is currently in progress, with encouraging results, and the authors fully expect the HOM BPM system to be suitable for inclusion in the ILC.

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