HIGH PRECISION SC CAVITY DIAGNOSTICS WITH HOM MEASUREMENTS

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Abstract

Experiments at the FLASH linac at DESY have demonstrated that the Higher Order Modes induced in Superconducting Cavities can be used to provide a variety of beam and cavity diagnostics. The centers of the cavities can be determined from the beam orbit which produces minimum power in the dipole HOM modes. The phase and amplitude of the dipole modes can be used as a high resolution beam position monitor, and the phase of the monopole modes to measure the beam phase relative to the accelerator RF. Beam orbit feedback which minimizes the dipole HOM power in a set of structures has been demonstrated.

For most SC accelerators, the existing HOM couplers provide the necessary signals, and the downmix and digitizing electronics are straightforward, similar to those for a conventional BPM.

THE DESY FLASH LINAC

The experiments described were performed on the FLASH (Free Electron Laser in Hamburg) superconducting linac at DESY [1]. FLASH# is also used as a test facility for the International Linear Collider (ILC) and the X-ray Free Electron Laser (XFEL) under the name TESLA Test Facility – Phase 2 (TTF2). FLASH contains 5 accelerating cryo-modules, each composed of 8 cavities, each 1 meter long, and containing 9 cells. The machine operates at a fundamental frequency of 1.3 GHz, with a typical energy between 450 and 700MeV, and approximately 1 nano-Coulomb charge.

Each cavity has 2 couplers used to damp the higher order modes (HOM), and cables to bring the HOM power out to room temperature. The typical damped Q of the HOM modes is 10^5.

HIGHER ORDER MODES IN SC ACCELERATOR CAVITIES

In addition to the fundamental accelerating mode, Superconducting Cavities (SC) support a spectrum of higher order modes. While HOMs can be a source of a variety of accelerator problems: beam breakup, heating, etc. they can also be used as beam and cavity diagnostics.

Mode Coupling to the Beam

HOMs can be characterized by their azimuthal dependence as “monopole”, “dipole”, or higher multipole modes. Here we consider the response of these modes to a single electron bunch propagating near the axis of the cavity, and we assume bunches with lengths short compared with the wavelength of the HOM modes.[2]

Monopole modes have no first order variation with the beam offset from the axis of the cavity, and are excited with amplitudes proportional to the charge in the bunch and with phase determined by the arrival time of the bunch.

Dipole modes occur in doublets with orthogonal polarizations, with a frequency splitting caused by asymmetries due to the cavity couplers, and fabrication imperfections. Dipole modes are excited with an amplitude proportional to bunch charge, and to:

- Transverse position relative to the cavity axis
- Transverse angle relative to the cavity axis. The strength of this coupling relative to the position coupling is given by a mode “effective length”, on the order of the cavity length. This signal is excited at 90 degrees phase relative to the position signal.
- Bunch tilt, with amplitude proportional to the bunch length, and 90 degrees phase relative to the position signal. For the short bunch length in FLASH this signal is not significant.

HOMs as Diagnostics

In most superconducting linacs, and in FLASH in particular, the HOM modes must be damped with special couplers to prevent beam instabilities. The HOM signals are transported outside of the tunnel and are thus available for use without requiring any additional beam line components.

The HOM monopole modes provide a measure of the beam phase in the cavity, while the dipole modes provide a measure of the beam position relative to the mode axis. It must be noted, however that the HOM mode axis may not be aligned with the physical axis of the cavity.

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#Until recently FLASH was known as the VUV-FEL

HOM Modes in FLASH

The FLASH cavity HOM frequencies were simulated [2], and have been measured [3]. Of particular interest for diagnostics are the second monopole band at 2.38 to 2.45 GHz, and the first dipole band at 1.63 to 1.89 GHz.

The monopole modes TM011-8 and TM011-9 at 2.45 and 2.46GHz have strong coupling to the beam, with simulated (R/Q) ~70 Ohms

The dipole TE111-6 at 1.7 GHz was used for position measurements. This mode has a calculated (R/Q) of 5.5 Ohms/cm^2.

HOM MEASUREMENT SYSTEM

Two independent systems were used to study the HOM modes in FLASH [4]. A broadband (2.5GHz) system was used for monopole mode based beam phase measurements. This system directly digitized the HOM signals with fast oscilloscopes.

A narrowband (20MHz) system, centered at the TE111-6 frequency of 1.7GHz was used for dipole mode based beam position measurements. This system down-mixed the HOM signal to an approximately 20Mhz IF, which was then digitized by high resolution digitizers.

MONOPOLE MODES FOR BEAM PHASE MEASUREMENT

Superconducting Linac based FELs, and the International Linear Collider require control of the main RF phase relative to beam time at the 0.1 degree level. Measurement of this phase is complicated by drifts in the cables and measurement electronics.

The HOM couplers in the FLASH linac have superconducting filters to reject the 1.3GHz accelerating mode, however the leakage of that mode through the coupler is comparable in power to the HOM monopole mode signals. This allows a simultaneous measurement of the 1.3GHz accelerator mode and of the beam induced monopole HOM modes using the same cables and electronics.

Monopole Signal Analysis

The HOM coupler signal, including the 1.3GHz fundamental leakage signal is digitized. Since the monopole lines are singlets, identification of the mode frequencies from the spectrum is straightforward. A typical monopole spectrum for one cavity is shown in figure 1.

The phase of the monopole lines can be measured, and used to define a precise beam time. The phase of the 1.3GHz fundamental can then be measured with respect to this time.

Phase Measurement Results

Figure 2 shows a measurement of the 1.3GHz phase during a 5 degree phase change commanded by the RF control system.

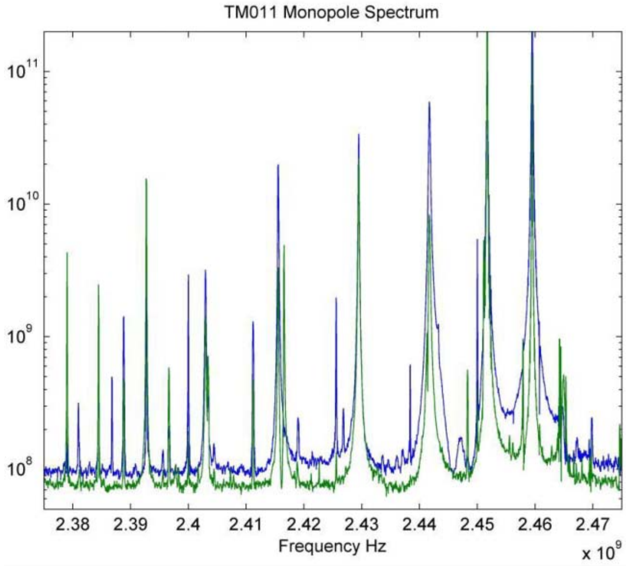

Figure 1: Monopole Spectrum, both couplers.

The measurement noise is estimated by comparing the measured beam relative to RF phase from the 2 couplers on a single cavity. The difference, after subtracting a phase offset, corresponds to a 0.08 degree (1.3GHz) measurement noise.

Interestingly, when the beam relative to RF phases of 2 cavities on the same klystron are compared, an approximately 0.3 degree variation is measured. This could be due to microphonics, or Helium pressure differences between the cavities.

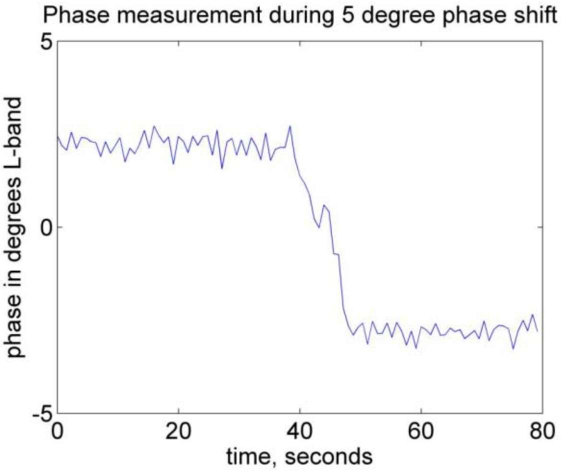

Figure 2: Measured main RF phase relative to beam phase from HOMs during a 5 degree phase shift.

DIPOLE MODES FOR BEAM ORBIT MEASUREMENT

Superconducting Linac based FELs and the ILC require beam orbit measurement at the micron level. Cavity BPMs can provide resolutions better than 20 nanometers

[5]. HOM dipole modes can be used in a fashion similar to cavity BPMs, although at poorer resolution as the cavities are not optimized for this purpose. The HOM measurements have the advantage that the majority of the linac length is occupied by accelerator structures.

Dipole Mode Signals

Each of the dipole modes contains two lines with a splitting, in the FLASH linac, comparable to the line width. Some typical dipole signals are shown in figure 3.

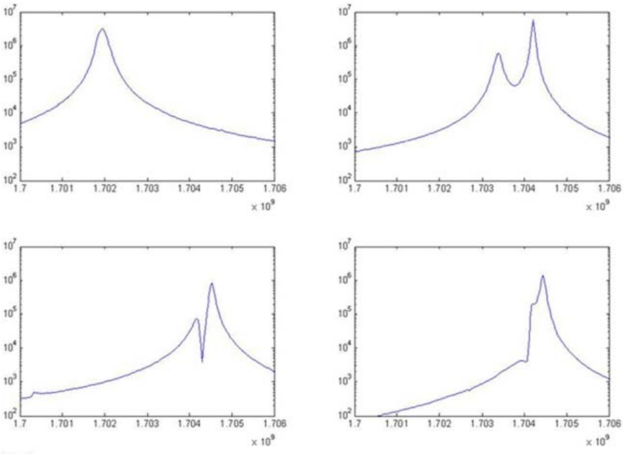

Figure 3: HOM dipole spectra for different cavities showing splitting of polarizations.

It has proven difficult to fit to these signals to obtain the frequencies of the 2 lines in the dipole mode. Instead Singular Value Decomposition (SVD) is used to find an orthonormal basis for the data sets. The amplitudes of the strongest 6 modes (for some analyses 8 modes are used) are measured for each machine cycle. Linear regression is then used to correlate these mode amplitudes with the beam position measured by conventional BPMs. This method is described in [4].

Beam Position Measurement Results

The beam was steered over a range of approximately 5mm in X and Y, and the HOM mode amplitudes calibrated relative to the measured positions using the configuration shown in figure 4.

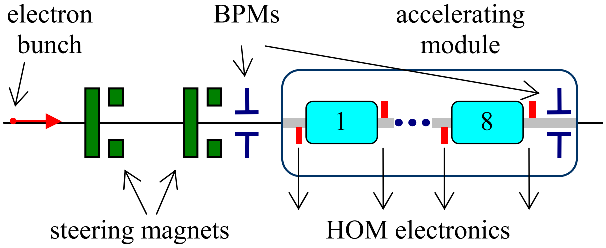

Figure 4: Steering Setup for HOM dipole experiment.

Pulses with saturated HOM signals, low beam current, or bad orbits as measured by the conventional BPMs were rejected. The position measured by the middle cavity of the accelerator module was compared with the positions predicted by the end cavities as a measurement of the HOM position resolution. The results are shown in figure 5.

For the large steering used, the circular error was 24 microns, corresponding to a resolution of 20 microns for a single cavity. When a smaller steering is used, the single cavity resolution in Y is 1.5 microns, and 5 micro-radians RMS.

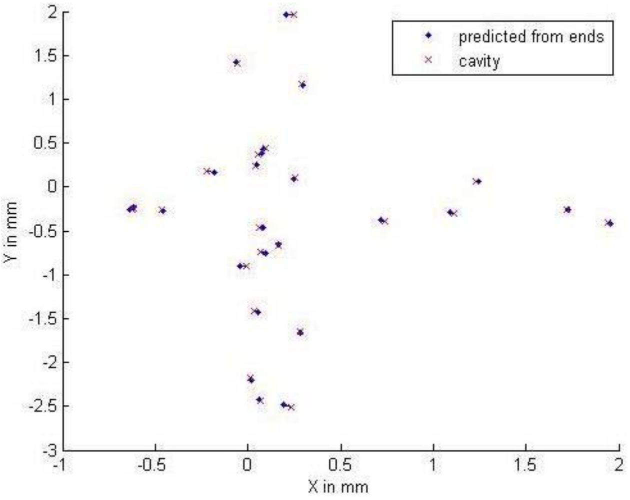

Figure 5: HOM beam position measurement from end cavities and middle cavity. RMS circular error is 24 microns.

Resolution Limits

The theoretical position resolution of the HOM modes is limited by thermal noise. Here we assume the electronics is at room temperature, although in principal cryogenic electronics could be used. The energy deposited by a beam into a cavity is given by [6]:

$$U = \left(\frac{R}{Q}\right)\frac{\omega}{2}q^2$$

This is to be compared with the minimum detectable thermal energy

$$U_{th} = \frac{1}{2}k_b t$$

For a 1 nC beam this corresponds to a thermal noise limited resolution of 3 nanometers.

For the system installed at FLASH, the HOM cable losses are approximately 10dB (for studies in the cryo-module presented here). In addition, 10dB of attenuators were added to the input of the electronics to increase the dynamic range and reduce the chance of electronics damage from RF breakdowns. The measured electronics noise figure is 6.5dB. Combining these factors produces a predicted resolution of 65 nanometers, in comparison with the best observed resolution of 1.5 microns.

We believe there are two primary causes for this discrepancy, both related to the beam orbit during the measurement being on the order of a millimeter from the mode center:

- In order to measure position, the HOM signals must be normalized to the beam current. Micron noise at millimeter offsets requires a current measurement linearity and noise < 0.1% RMS. It is not known if the FLASH current measurement met this requirement.
- The Local Oscillator used to frequency shift the 1.7 GHz HOM modes to the 20 MHz IF signal for the digitizers was discovered after the experiment to have abnormally high phase noise (~1 degree RMS). This is sufficient to mix the angle and position HOM signals and degrade the resolution to the level measured.

Future experiments will investigate the resolution limits of the measurement.

HOM Based Feedback

After the correlation between HOM mode amplitudes and beam position has been measured, it is possible to construct a first order beam feedback to minimize the total HOM power in a module. A test run of this type of feedback, operating in the first accelerator module is shown in figure 6. The amplitudes of the TE111-6 modes in the 8 cavities of the first module are shown. Note that this experiment used an earlier version of the HOM measurement system.

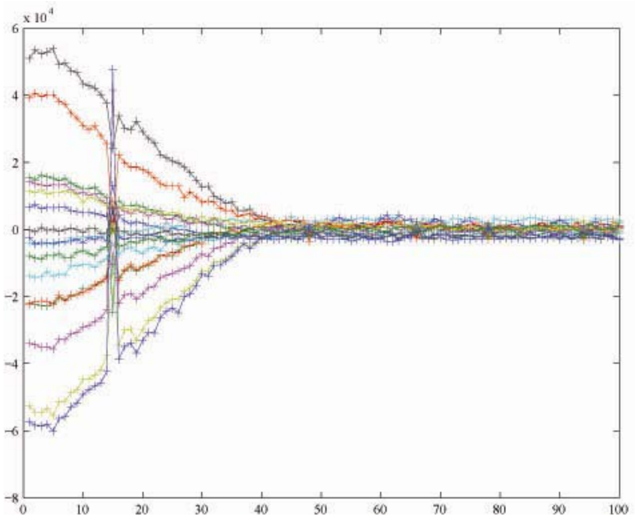

Figure 6: HOM mode amplitudes for 100 machine cycles after feedback is turned on in first accelerator module.

CAVITY ALIGNMENT MEASUREMENT

There exists an orbit through each cavity which will null the HOM power for a particular dipole mode. The beam X and Y (but not X angle and Y angle) were found which minimized the HOM power in each of the cavities of a structure. The relative positions of these minima for each cavity of the module were used to measure the alignment of the module.

Algorithm to Find Orbit with Minimum HOM Power.

As described above, SVD can be used to find the 6 strongest HOM mode amplitudes. Linear regression can then be used to correlate these amplitudes with beam position. The position corresponding to the minimum of the sum of the squares of these amplitudes can then be calculated.

Cavity Alignment Measurement Experiment

The beam was steered in X,Y,X',Y' in the fourth and fifth modules (ACC4 and ACC5). Approximately 20 runs, of ~100 points each were used. The alignments are plotted with the slope and offset removed to show the relative alignment of the cavities within the module, figure 7 and figure 8.

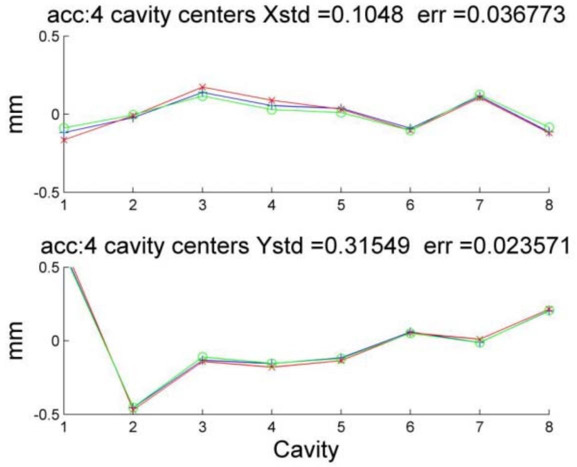

Figure 7: Alignment of TE111-6 cavity mode centers in module 4.

In ACC4, the RMS alignment in X and Y was 105 and 215 microns, with a measurement reproducibility in X and Y of 37 and 24 microns.

In ACC5, the RMS alignment in X and Y was 241 and 203 microns, with a measurement reproducibility of 9 and 5 microns. The specification for cavity alignment is 500 microns RMS.

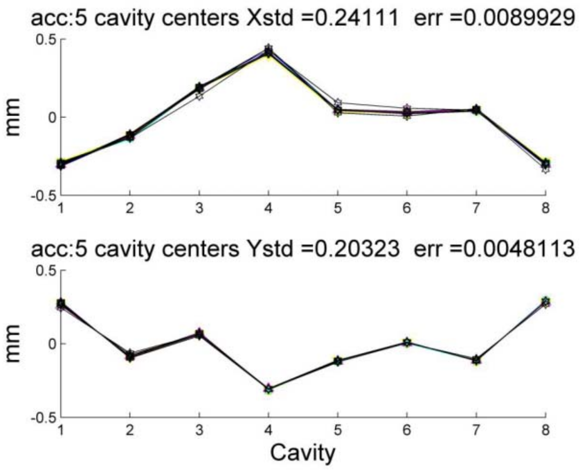

Figure 8: Alignment of TE111-6 cavity modes centers in module 5.

The HOM based cavity alignment measures the relative positions of the axes of the TE111-6 dipole modes in the cavities in a module. The dipole mode axes may not be aligned to the mechanical centers of the cavities due to perturbations from couplers, and manufacturing imperfections.

FUTURE WORK

Multi-Bunch Operation

The HOM experiments to date on FLASH have used single bunch beam. For bunch rates not much faster than the HOM mode decay times, bunch by bunch position and phase measurements should be possible.

- The system is linear
- The data acquisition (for FLASH) is synchronous with the bunch train
- It is possible to calibrate the effect of a bunch on the signals for the following bunch.
- Using this calibration, can de-convolve the single bunch response from the train.

Cavity Diagnostics

The existing broadband HOM diagnostic system can measure the response of all of the HOM modes below 2.5GHz to beam position and angle. This will allow detailed comparison of cavity simulations.

SUMMARY

To date, the HOM measurements at FLASH have demonstrated:

- Beam vs. RF phase measurement to < 0.1 degree L-band
- Beam position resolution of 1.5 Microns, 5 micro-radians.
- Cavity alignment measurement within a module to 10 microns RMS.
- HOM based feedback to minimize HOM power in a module.

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