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Electronics and Algorithms for HOM Based Beam Diagnostics

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Abstract. The signals from the Higher Order Mode (HOM) ports on superconducting cavities can be used as beam position monitors and to do survey structure alignment. A HOM-based diagnostic system has been installed to instrument both couplers on each of the 40 cryogenic accelerating structures in the DESY TTF2 Linac. The electronics uses a single stage down conversion form the 1.7 GHz HOM spectral line to a 20MHz IF which ahs been digitized. The electronics is based on low cost surface mount components suitable for large scale production. The analysis of the HOM data is based on Singular Value Decomposition. The response of the OM modes is calibrated using conventional BPMs.

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HIGHER ORDER MODE SIGNALS IN SUPERCONDUCTING ACCELERATOR CAVITIES

The passage of an electron bunch through a superconducting cavity in addition to coupling to the accelerating mode, will excite a spectrum of higher order modes[1]. The dipole mode amplitudes contain information on the beam position relative to the cavity[2], while the monopole modes provide information on the arrival time of the beam. A fully relativistic beam will most strongly excite the cavity modes with near speed of light phase velocities, and we only consider such modes.

The amplitude of the dipole modes excited by a beam position offset is $A = C_x qx$ where q is the bunch charge, x is the position offset relative to the mode center, and C_x is a coupling constant. Dipole modes are also excited by a bunch which traverses the cavity at an angle with amplitude $A = C_\theta q\theta$ where θ is the beam angle relative to the mode axis, with a phase 90 degrees from that produced by a position offset. A

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tilted bunch will also excite dipole modes with an amplitude $A = C_t q a l_b{}^2$ where a is the bunch angle, and l_b is the bunch length (assumed short compared with the mode wavelength). For the TTF2, the bunch length is sufficiently short that the “tilt” signal is insignificant.

The HOM mode spectrum for the TTF cavities is described in [3].The two dipole modes with the strongest coupling to the beam are the TE111-6 and TE111-7. For the HOM dipole experiments the TE111-6, with a frequency of approximately 1.7GHz was used. The dipole modes including the TE111-6 are doublets, with a frequency splitting caused by the asymmetry in the cavity shape, and by the cavity power coupler. Several TM011 monopole lines were used for the HOM monopole experiment.

For this paper we concentrate on single bunch operation, however the analysis can be extended to multi-bunch beams

EXPERIMENTAL SETUP AT DESY

TTF2 Linac

The TTF2 linac[4] at DESY operates at 1.3GHz, and contains 5, 8-cavity accelerating structures, each cavity approximately 1.2 Meters long, and containing 9 cells. Although the TTF2 is capable of operating with millisecond bunch trains, for the HOM experiments, it was operated single bunch, with a typical charge of 1 nano-Columb. A block diagram of the TTF2 is shown in figure 1.

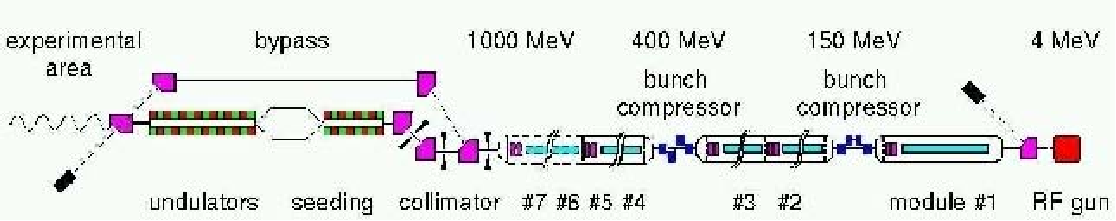

FIGURE 1. TTF2 Linac, Structures 1-5 currently installed

The TTF2 conventional BPMs (both strip-line and cavity) were used to measure the beam orbit. Toroids or BPM sum signals were used for signal normalization. Many of the TTF2 conventional BPMs have resolutions of a few microns[5].

Each cavity has 2 couplers, located and opposite ends, and at a 115 degree relative angle to provide damping of the HOM modes. The signals from these couplers are brought out to room temperature, and cabled to a control area outside of the tunnel. The approximately 10dB losses in the cables provide adequate damping of the HOM modes, even if un-terminated.

The data described here is from a series of experiments in March 2006. The beam was steered by a large amount (~1 cm) relative to its nominal orbit, in order to be sure to pass through the centers of the cavities.

HOM Dipole Mode Data Acquisition System

The basic principal of the HOM Dipole front end electronics as shown in figure 2, consists of a band pass filter to select the 1.7GHz TE111-6 mode, which is then down mixed to an approximately 20MHz IF, and digitized. The DESY 1.3GHz fundamental RF is produced as the X144 harmonic of a 9.0275MHz reference. The Local oscillator (1.679GHz) is the X186 Harmonic of the 9.0275MHz, and the digitizer clock is the 12X harmonic.

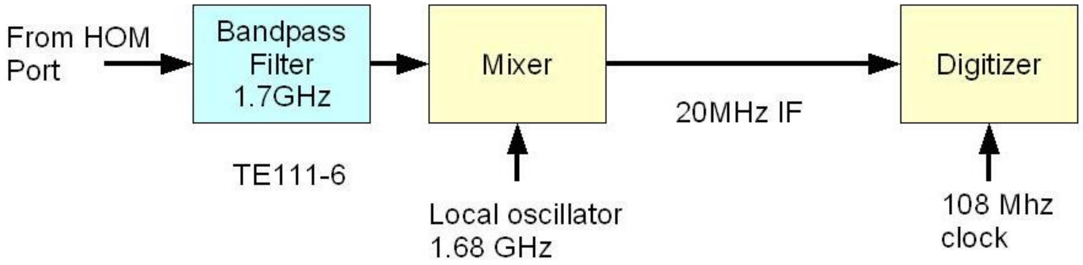

FIGURE 2. HOM down mix electronics

The TE111-6 HOM mode frequencies for the different cavities range approximately +/-10MHz around the nominal 1.7GHz, resulting in an IF range from 10-30MHz, within the first Nyquist band for a 108MHz digitizer. The decay times of the HOM modes vary with their coupling, but are typically a few microseconds.

A pair of down mix circuits on a single PC board is used to measure both signals from each cavity. Since the HOM modes have arbitrary coupling to each coupler, channel to channel crosstalk on a board is not relevant. The signals for each structure are processed by a rack chassis containing eight down mix boards. A detailed block diagram of the HOM electronics is given in figure 3.

An input coupler provides a test port for the HOM signals for other experiments. A second coupler is used to introduce a calibration signal at 1.697GHz (the X188 harmonic of the 9.0275MHz reference) to measure the electronics gain and phase. A 2 section ceramic filter is used to attenuate signals outside of a 20MHz bandwidth of 1.7GHz mode frequency to prevent amplifier saturation.

A RF limiter, rated at 100W peak power is used to protect the downstream active electronics. Note that any leakage of the cavity fundamental power near 1.3GHz will be blocked by the passive band pass filter.

A low noise (1.1dB NF), high linearity (27dBm OIP3) preamplifier is used, followed by a 4 section, 20MHz bandwidth ceramic filter. This second filter blocks all frequencies which might alias into the signal band. A high linearity mixer (30dBm IIP3) is used to mix the signal down to the approximately 20MHz IF.

The mixer is followed by 2 stages of IF amplifier to drive the required +/-1V, 50 Ohm input of the digitizer. A low pass filter at 36MHz is used to prevent amplifier noise from aliasing into the signal band.

The digitizer is a Struck Innovative Systems[6] SIS3301, 8 channel, 14 bit, VME digitizer, operating at 108Ms/s. Data is collected from the digitizer with the DESY DOOCS [7] control system, and processed offline using Matlab.

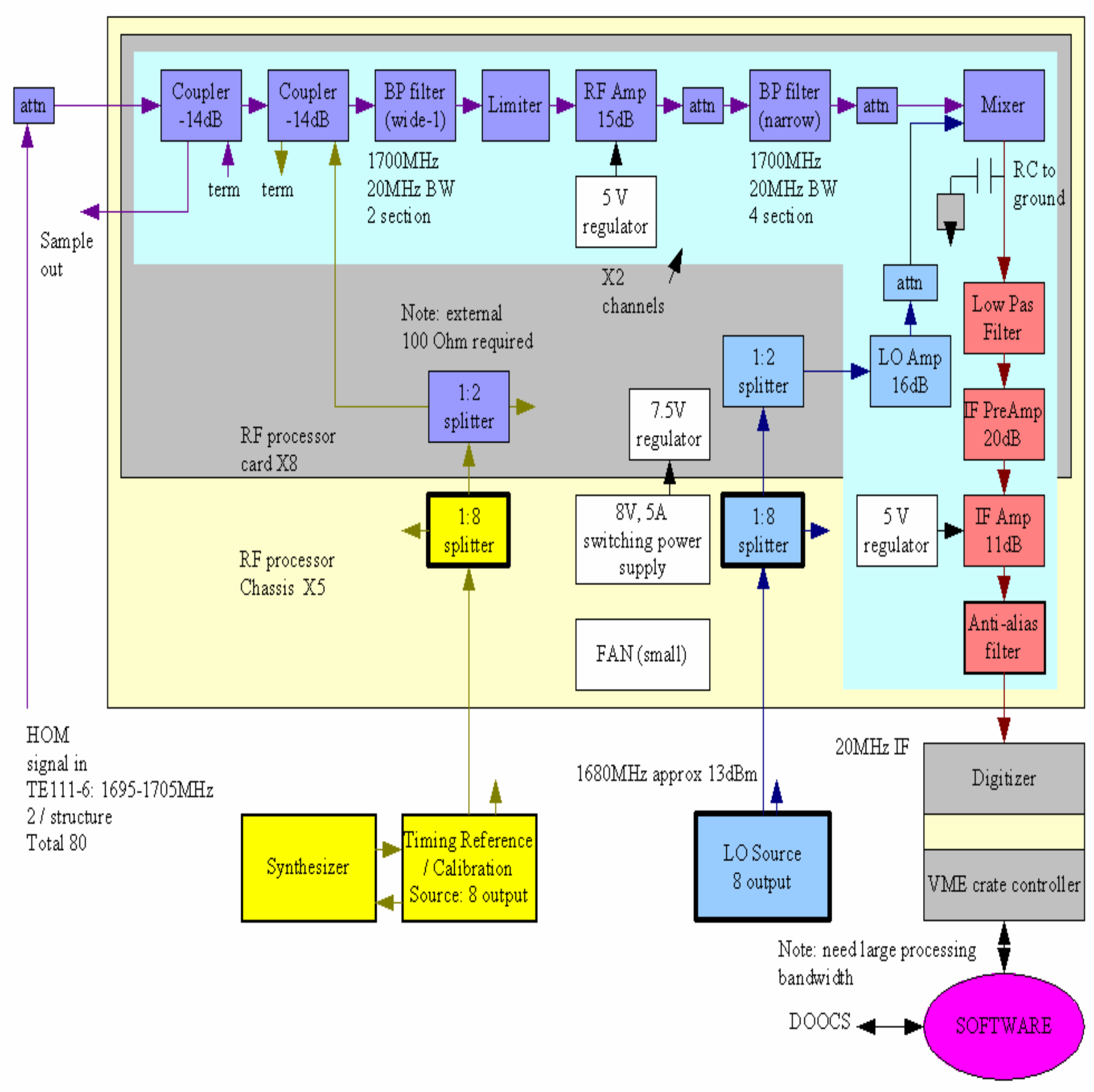

FIGURE 3. HOM electronics detailed block diagram.

Due to the large HOM signals produced by the large beam steering during the experiment, 10dB attenuators were added to the input of the electronics. This provides better measurement range, but is expected to degrade the system resolution by approximately X3.

Dipole HOM Data Analysis

The raw signals from each of the HOM couplers, band pass filtered to only pass the 1.7GHz TE111-6 doublet have the form of 2 interfering, decaying sine waves as shown in figure 4. Also shown are some typical power spectra from the dipole mode doublets. Note that the line separation is on the order of a line width, and the lines may be partially or completely degenerate.

The most obvious analysis method would be to find the signal amplitudes at known mode frequencies, and correlate these against the beam position. With the spectra shown in figure 4 however, it is difficult to automatically determine the mode frequencies and a different method based on singular value decomposition was used.

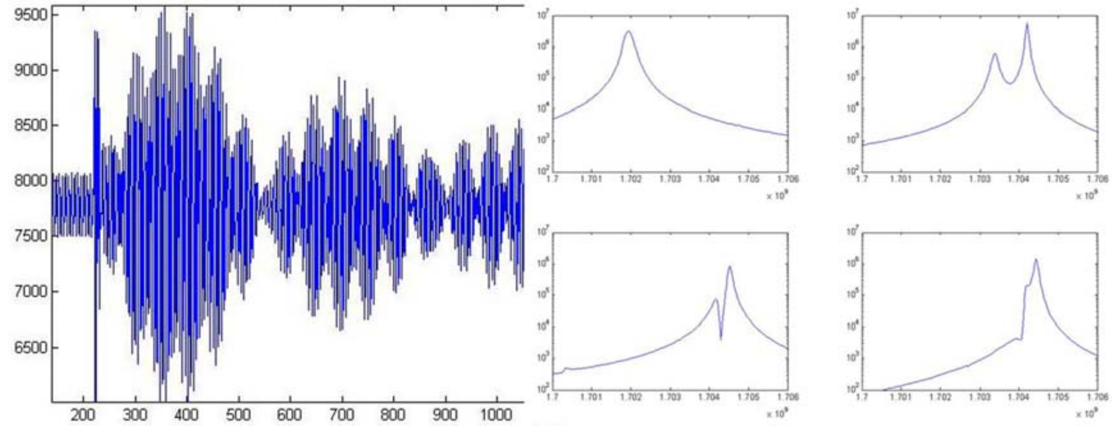

FIGURE 4. Sample waveform, and typical power spectra for dipole mode doublets.

Singular Value Decomposition

Singular value decomposition (SVD) is a mathematical technique for finding the normal modes of a system. In particular, given a matrix D, it finds matrices U, S, and V such that $D = USV^T$, with U and V unitary, and S diagonal. Four out application, if each row of D represents a waveform, then the rows V will provide an orthogonal basis set (modes) for D, with the average amplitude of each basis mode proportional to its associated diagonal element of S. A description of the use of SVD for determining normal modes for accelerator beams is given in [8]. Note that the "modes" found by SVD may be linear combinations of the physically intuitive modes. For this analysis, SVD was performed using the Matlab svds function, which finds a specified number of largest SVD modes. For our analysis, the largest 6 modes were used. We refer to these as "SVD modes" to reduce confusion with the physical HOM modes.

Data Preparation / SVD

As some of the HOM dipole doublets are degenerate in frequency, it is necessary to use both couplers on the cavity to measure the two mode amplitudes. In order to apply SVD to find the modes we append the signals from the 2 couplers. Due to the large steering used for this experiment, the majority of beam pulses resulted in saturated signals. We chose a fixed analysis window which avoided the saturated early part of the pulses. Eliminating the early large amplitude part of the pulse is expected to reduce the resolution of the system for small position offsets. The experiments were performed with single bunches, and a record length of 4000 points (approximately 4usec) was used. The combination of the 4000 point record from each of 2 couplers for a cavity resulted in 8000 point inputs to SVD.

The HOM signals for each data set, a series of typically 250 machine pulses, were recorded. Figure 5 shows a sample use of SVD data analysis to extract modes. It is interesting to note that the calibration tone appears in modes 1 and 2 (figure panels 2, 3) but, as expected, not in the mode combinations corresponding to X and Y.

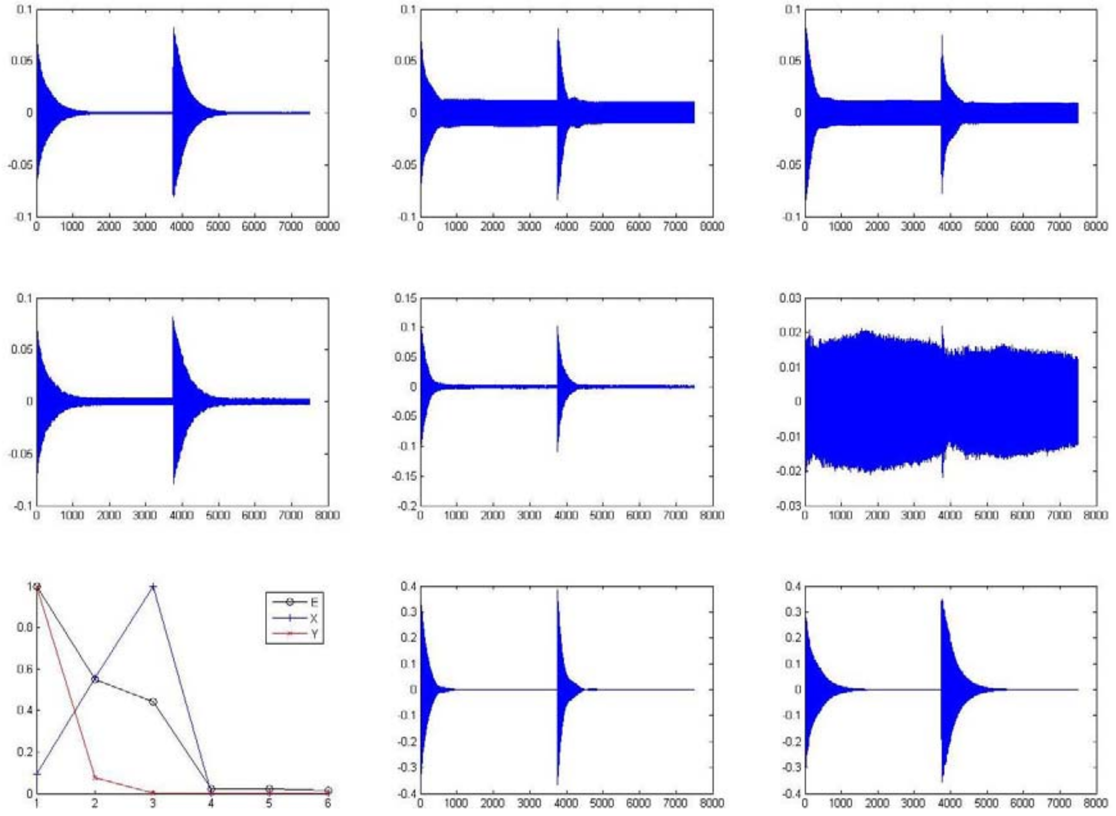

FIGURE 5. SVD analysis: Panel 1: Raw data (signals from 2 couplers appended). Panel 2-7, show the 6 SVD modes with the largest Eigen values. Panel 8 shows the Eigen values, and the contribution of the modes to the measured X and Y position. Panel 8,9 show the combination of the modes corresponding to X and Y.

Mode Amplitudes

The modes found by SVD are a set of orthonormal vectors of the same length as the data record (8000 points). After the modes have been found for one data set the mode amplitudes for another (or the same) data set can be found by the dot product of the mode vector and the HOM data, in our case resulting in 6 mode amplitudes for each cavity, for each machine cycle. $A_{(cycle,mode)}=V_{(datapoint,mode)}*D_{(cycle,datapoint)}$ We use one "calibration" data set to find the SVD modes, than use those modes to find the mode amplitudes for the other data sets. Note that these mode amplitudes are similar in concept to the Fourier amplitudes that would be found in a conventional frequency analysis.

Linear Regression to Find Positions

The HOM dipole modes axis have an arbitrary rotation relative to vertical, and have unknown couplings to the beam. The transformation between the SVD mode amplitudes and beam position is found from linear regression against the conventional BPMs as follows.

We use the conventional TTF2 BPMs to calculate the position of the beam at each cavity. For each cavity, and each axis (x,y), we form a vector "B_{meas}", consisting of the position at the cavity for each machine pulse in the data set .

As the HOM amplitudes are expected to be proportional to bunch charge X position, we normalize the SVD HOM amplitudes to the bunch charge reported by the TTF2 control system (from a torroid or BPM sum). For a given data set, for each cavity we form a matrix "A" where each row is the (6) normalized SVD HOM amplitudes for a specific pulse, with a row for each machine pulse. We add a column of '1s' to the matrix to allow for a DC offset in the beam position. We want $A*X=B_{est}$, where X is a vector which when multiplied by the SVD HOM amplitudes A, gives the best estimate of the beam position B_{meas}. X is found using the Matlab mldivide function, which performs the linear regression. Note that there is a separate vector X for each axis (x,y). The set of vectors X is found for the calibration data set, and then applied to the other data sets.

Monopole HOM Mode Data Acquisition

A simple data acquisition system was constructed to evaluate the use of monopole HOM modes as a beam phase monitor. The system was based on a fast (5Gs/s), 4 channel oscilloscope with input filters and amplifiers as shown in figure 6. The oscilloscope was triggered from a source locked to within 50ps RMS of the beam time.

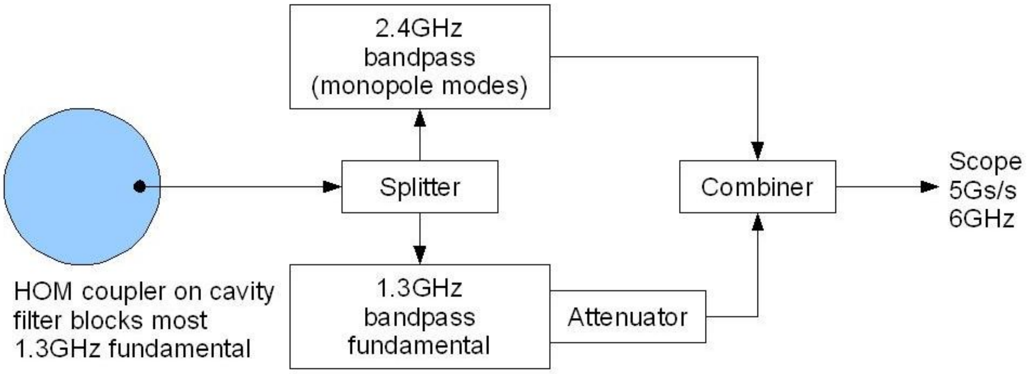

FIGURE 6. Electronics for monopole modes. Typical attenuation to match fundamental and monopole amplitudes was 20dB

The oscilloscope was able to simultaneously digitize on the same channel, the leakage of the fundamental power in the cavity through the HOM port, and the monopole modes excited by the beam. A typical monopole spectrum is shown in figure 7. Typically 100,000 points were used, (20 microseconds) in the analysis.

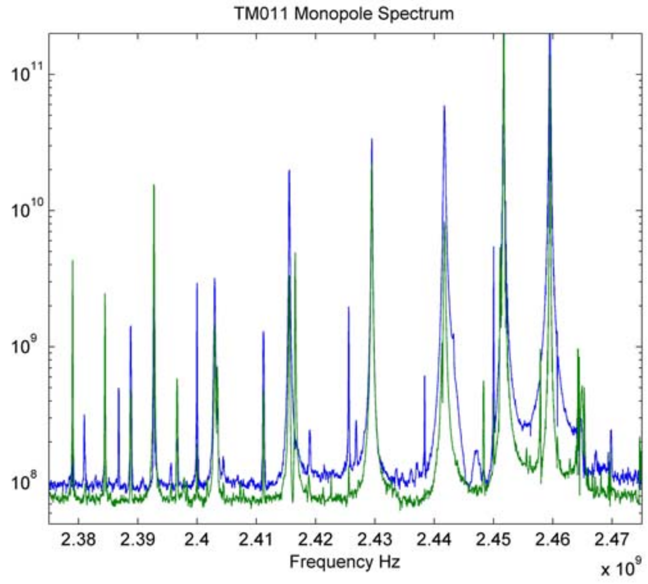

Figure 7. Monopole spectrum overlaid for 2 couplers

Monopole HOM Mode Data analysis

The analysis of the monopole data is much more straightforward than for the dipole data. The monopole lines are singlets, so their frequencies can be found easily. In addition the monopole modes are detected by both HOM couplers on a cavity, so only one coupler is required for phase measurements.

Using the known frequencies, the phase of each of the monopole lines can be determined with respect to the trigger time for the oscilloscope. The hardware trigger to the oscilloscope has sufficient stability (~50 picoseconds RMS) to remove uncertainty in selecting the correct cycle of each mode. The mode phases can then be used to provide a fine correction to the trigger time. The power weighted average of the time determined by each of the HOM modes is used.

The phase of the 1.3GHz fundamental is then measured with respect to this time. As the same cables are used to convey the fundamental signal, and the HOM signals, it is expected that this measurement would be insensitive to cable length changes due to temperature. Note that this is a relative measurement, there is an unknown overall phase offset.

PRELIMINARY RESULTS

Analysis of the data is still ongoing, however a preliminary set of results indicating good performance for both the position measurements based on the dipole modes, and phase measurements based on the monopole modes have been obtained. Data analysis was performed off-line, however the algorithms used could be converted for use in a real time DAQ system or in programmable logic.

Beam Position Measurement With Dipole HOM Modes

A series of data sets were taken, with the beam steered over a range of a few millimeters in X, and Y in all of the cavities of the TTF2. The SVD modes, and correlations between modes and beam positions were found as described above. Then the positions measured by the end cavities of the structure (ACC5) were used to predict the position in the middle cavity. The resulting 24 micron RMS circular error includes both noise and nonlinearity over an approximately 5 millimeter steering range. Results are shown in figure 8.

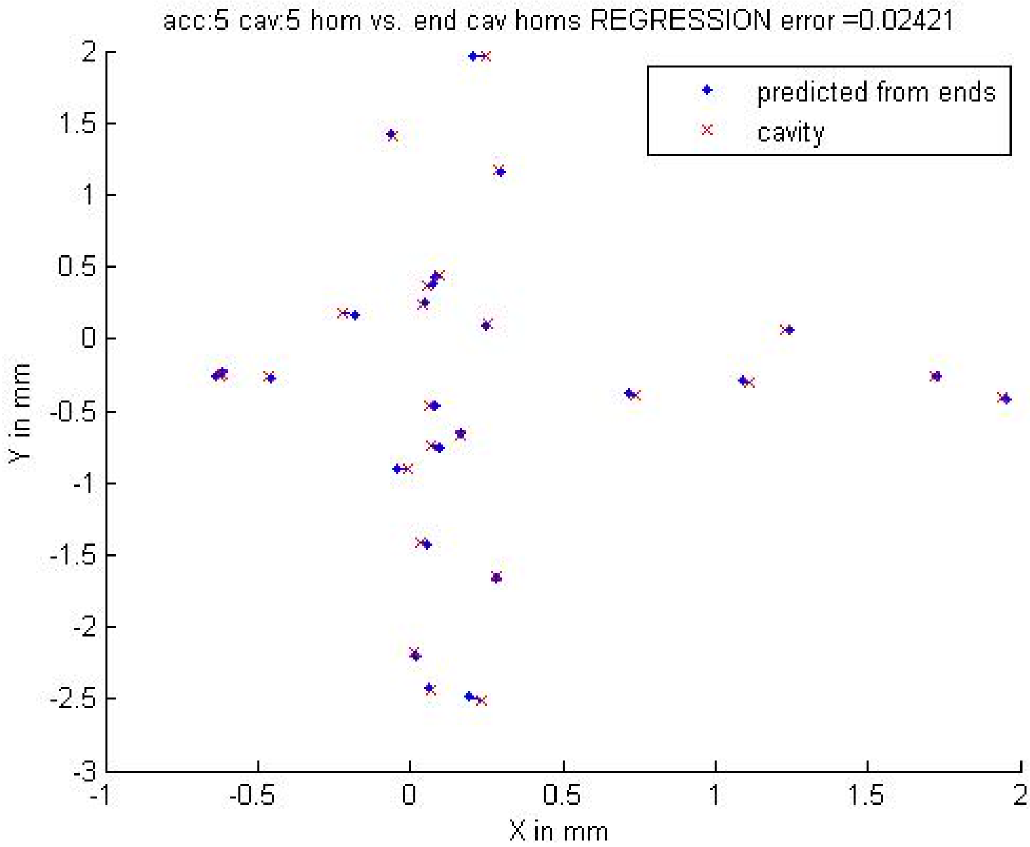

FIGURE 8. Dipole HOMs used as BPMs. Calibrated position from end cavities used to predict position for center cavity of ACC5.

When a shorter range scan (~600 microns) is used, a RMS difference of 7 microns is seen (corresponding to ~5 microns resolution), as shown in figure 9. Note without the 10dB attenuators a factor of 3 resolution improvement is expected.

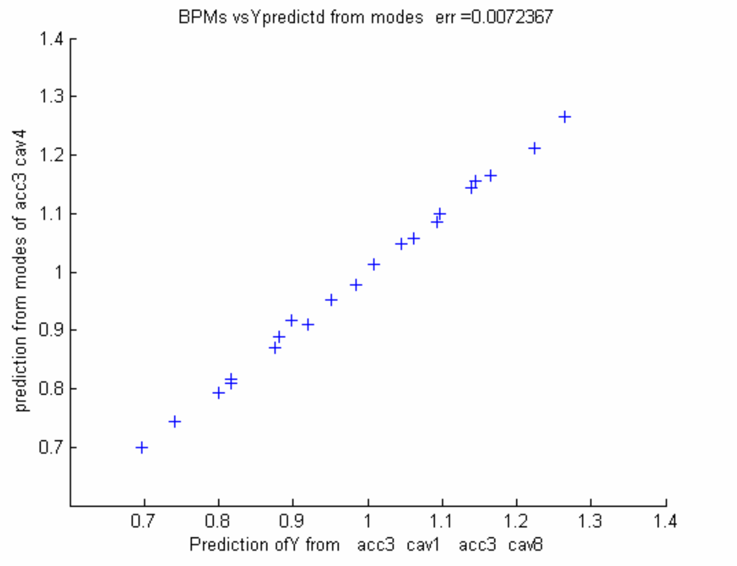

Figure 9. Dipole HOM modes to measure beam position for a small steering range

Cavity Alignment From HOM Dipole Modes

The analysis described above determines the correlation between SVD mode amplitudes and beam position. From this it is possible to find the beam position corresponding to the minimum HOM mode power, allowing an in-situ measurement of the cavity alignment. Figure 10 shows this alignment for ACC5, measured with 14 independent data sets. They show a RMS cavity alignment of approximately 200 microns, with a RMS measurement reproducibility of <10 microns.

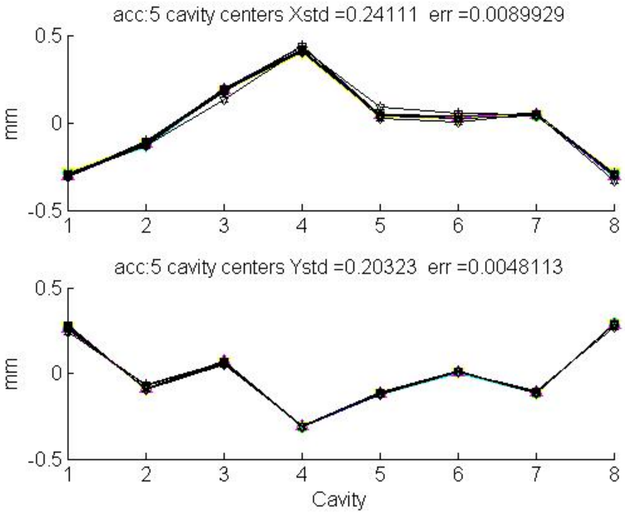

FIGURE 10. HOM TE111-6 dipole mode centers for the cavities in ACC5, 14 independent measurements shown.

Beam Phase Measurement Using Monopole Modes

The beam phase relative to the fundamental RF was measured in 2 cavities (cavity 5 and cavity 6) of ACC1 while the TTF2 control system commanded a 5 degree change in the RF phase. The measured phase change agreed with the 5 degree shift, with a RMS difference between the 2 cavity measurements of 0.3 degrees of 1.3GHz (corresponding to a single measurement resolution of 0.2 degrees). The phase plot is shown in figure 11.

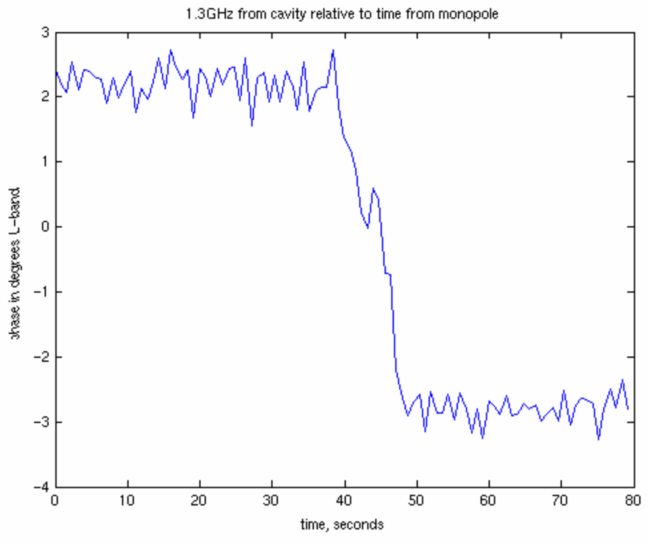

FIGURE 11. Phase measurement using monopole HOM signals during a 5 degree phase shift.

SUMMARY

Dipole HOM modes have been show to be usable as beam position monitors with ~5 micron resolution, expected to improve to <2 microns with the removal of input attenuators. The dipole modes also define a cavity "center" with a reproducibility of < 10 microns. Studies to correlate this center position with externally measured alignments are underway. The monopole HOM modes have been show to operate as a beam phase monitor with 0.2 degrees L-band (1.3GHz) resolution.

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