

CAVITY ALIGNMENT USING BEAM INDUCED HIGHER ORDER MODES SIGNALS IN THE TTF LINAC*

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Abstract

Each nine cell superconducting (SC) accelerator cavity in the TESLA Test Facility (TTF) at DESY [1] has two higher order mode (HOM) couplers that efficiently remove the HOM power [2]. They can also provide useful diagnostic signals. The most interesting modes are in the first 2 cavity dipole passbands. They are easy to identify and their amplitude depends linearly on the beam offset from the cavity axis making them excellent beam position monitors (BPM). By steering the beam through an eight-cavity cryomodule, we can use the HOM signals to estimate internal residual alignment errors and minimize wakefield related beam emittance growth. We built and tested a time-domain based waveform recorder system that captures information from each mode in these two bands on each beam pulse. In this paper we present a preliminary experimental study of the single-bunch generated HOM signals at the TTF linac including estimates of cavity alignment precision and HOM BPM resolution.

INTRODUCTION

Measurements at the TTF superconducting linac have demonstrated the use of higher order modes in the SC cavities to measure beam orbits on single bunch beams. The theoretical noise limited resolution is on the order of 10 nanometers at a one nanocoulomb bunch charge, so measurements should be practical at very low beam currents. The hardware required for a HOM based beam measurement system closely resembles the “digital down conversion” systems used in many conventional BPM systems.

Each cavity is provided with 2 couplers to damp higher order modes. The couplers located at each end of the cavity have a relative orientation of 115 degrees to provide damping for higher multipoles.

We discuss the extension of these techniques to multi-bunch beams, and to high repetition rate beams where there are no beam harmonics near the dipole mode resonances.

CAVITY HOM MODES

In addition to the fundamental accelerating mode, superconducting cavities support a spectrum of higher frequency modes [3]. Of particular interest for use as beam diagnostics are the modes in the first two dipole bands (TE111 and TM111 respectively) and first monopole band. Previously, power measurements on these modes have been used for beam alignment [4, 5], here we

describe the additional use of phase information to provide beam position measurements. In addition, the monopole modes provide a convenient signal for charge normalization and beam phase reference. In this paper we report the use of the amplitude and phase of sixth and seventh TE111 modes. As explained in [3], these modes couple strongly to the beam and are therefore ideal for position monitoring.

Dipole mode signals depend on beam transverse position (x, y), angle, and bunch tilt. The position signals are proportional to beam charge x position offset / effective cavity radius. Angle signals are proportional to the product of beam charge, beam trajectory angle and the effective cavity length. Bunch tilt signals are proportional to the product of beam charge, bunch tilt and bunch length [6]. Due to the short bunch length in the TTF2 (0.05 ps), bunch tilt signals are not significant for this experiment.

HOM RECEIVER SYSTEM

A block diagram of the electronics is shown in figure 1. The signals from the HOM ports are downmixed with the 1.3GHz accelerator reference signal, then digitized by a 5 Gs/S (real time), 8 bit, oscilloscope, which recorded 50,000 points / channel. The lack of anti-alias filter allowed the recording of the monopole HOM band which would otherwise have been cut off. Four simultaneously sampled channels were used, one for each of the 2 couplers on each of 2 cavities.

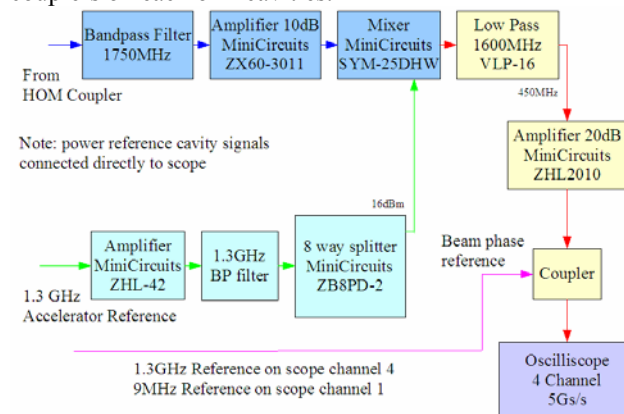


Figure 1: Block diagram of down mix electronics. For the data shown here, no anti-alias filter was used (the dashed-in 750MHz low pass filter), which resulted in extraneous monopole mode lines in the spectrum. The phase information in these lines proved quite useful. Ten dB of cable attenuation is included in the noise figure estimate.

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The raw signal on one channel, and the windowing function used for spectral analysis are shown in figure 2. The initial saturated part of the signal is eliminated in the analysis by the windowing function.

In order to measure the relative phase of signals with different frequencies a time reference is required, with a stability of a fraction of the frequency difference. With a HOM mode full passband frequency range on the order of a few hundred megahertz, and a requirement for phase measurements to a degree, a time reference stability of a few picoseconds is required.

In order to improve the precision of the TTF2 triggers, the accelerator 9 MHz master source and the 1.3 GHz RF reference signals were added to the downmixed signal. Beam intensity information based on the monopole HOM's was also used.

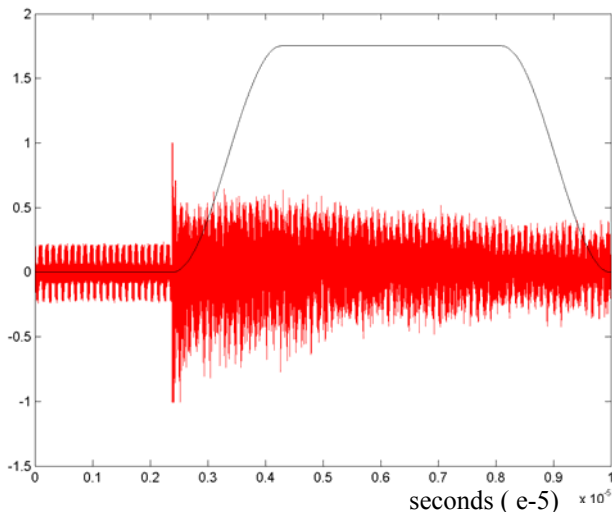


Figure 2: Raw signal at digitizer over a 10 μ s interval. The windowing function used for spectral analysis shown.

The spectrum (for cavity 8, averaged over all data acquisitions), with the HOM bands indicated, is shown in figure 3. Note that the mode frequencies are shifted down the 1.3GHz as a result of the downmixing with the accelerator reference signal.

HOM DATA

Beam Measurements

In order to remove the effects of incoming beam motion, simultaneous measurements from at least 3 cavities are required. The TTF2 was operated in single bunch mode for this experiment. The x and y correctors were steered over a range of ± 1 mm for the purpose of calibrating the HOM signals. At each of 9 corrector settings, HOM signals from 10 beam pulses were recorded.

Data Analysis

In general, each dipole HOM delivers power to both couplers in each of 2 polarization states. Thus we have 4 complex values Z_i ($i=1:4$, amplitude and phase) from each

cavity for each beam pulse. A calibration process (mentioned above) is required since neither the response amplitude nor the orientation of the mode polarization is known. Let M be the vector of Z for the roughly 100 beam pulses in a calibration sequence. For simplicity, assume we are only interested in displacement in one plane, x . There is a conversion vector R (with 4 complex entries) that we will determine through the calibration: $MR=X$. X in this case is the x corrector setting associated with the given pulse.

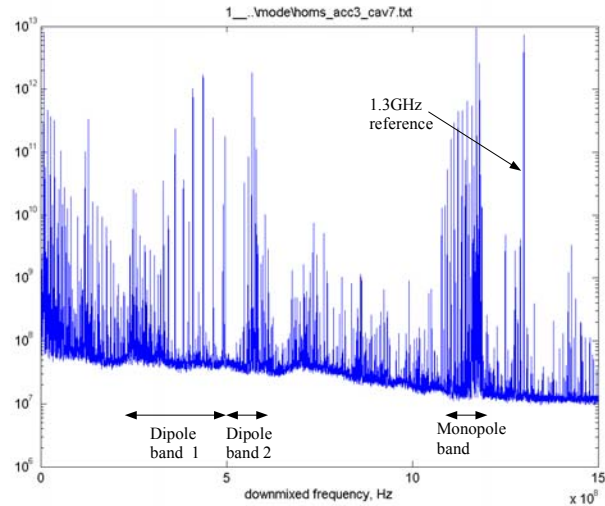


Figure 3: Averaged power spectrum for cavity 7, both couplers, all data acquisition cycles. Dipole band 1 (TE111) and dipole band 2 (TM111) and the ~ 2.5 GHz monopole band are shown. There are a total of 18 modes in the 2 dipole bands. The horizontal scale of the figure is offset by the LO frequency, 1.3 GHz.

This can be done independently for the vectors M associated with each instrumented cavity. The over-constrained vector R is determined through least-squares linear regression. We chose to estimate a second conversion matrix, Q , that connects the vectors from the cavities at the end of the cryomodule, $E=[M(1) M(8)]$ (cavities 1 and 8), with M from an internal cavity (2 through 7), $EQ=M$. The next step is to compare X as determined from the outer cavities with that determined from a given cavity: $X_{end}=EQR$ and $X_{mid}=MR$, for each machine pulse. The standard deviation of the pulse to pulse difference $\sigma = \text{std}(X_{end}-X_{mid})$ gives an estimate of the position measurement resolution.

The results described in this paper are based on analysis of the TE111-6 mode (~ 1700 MHz). Figure 4 illustrates the determination of one of the elements of Q , which is the slope of the line formed by the strongly correlated signals $M(2)$ and E . Figure 5 shows the pulse to pulse difference, $X_{end}-X_{mid}$, for this set of roughly 100 beam pulses. The apparent σ is about 4.5 microns. If we assume that this residual has equal contribution from cavities 1 and 2, this results in an estimate of the single cavity measurement resolution of about 3 microns.

Alignment and offset studies have yielded significant emittance improvements and will be reported [7].

Measurement Noise Limits

These measurements were performed with a system noise figure of approximately 10dB. The theoretical measurement noise, considering the known dipole mode coupling of approximately 10 Ohms/cm², and assuming a 10dB noise figure is approximately 60 nanometers. The factor of 30 between the theoretical and measured resolution is not yet understood.

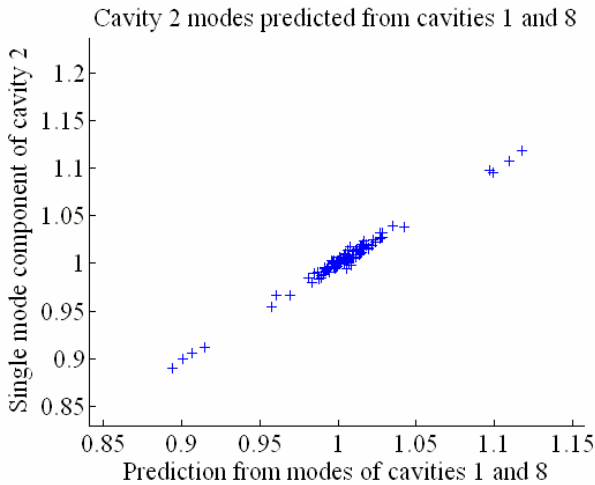


Figure 4: A component mode signal Z_i from cavity 2 vs those predicted through the regression fit $M=EQ$, from cavities 1 and 8.

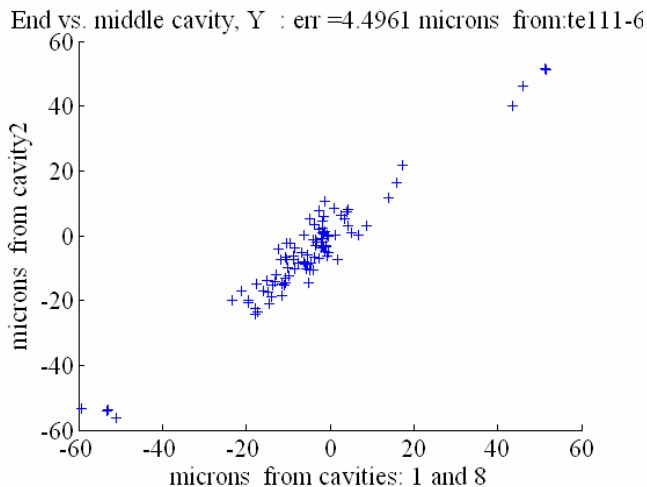


Figure 5: x predicted from the TE111-6 mode signals of cavity 2 vs that predicted from cavities 1 and 8 (at either end of the cryomodule). The width of the residual is approximately 4.5 microns, giving an estimate of the error associated with the measurement of a single cavity of about 3 microns.

PLANS

The April 2005 HOM experiment at the TTF2 used 2 fast oscilloscopes to allow simultaneous measurement of the HOM signals from 3 cavities. The signals from cavity 1 and 8 (the end cavities on a given structure) were filtered to pass only the TE111-6 mode. The signals from

both of the couplers from one of the remaining cavities will be digitized at 10Gs/s, with a 2.5GHz bandwidth, sufficient to directly measure all of the first 2 dipole bands and the first monopole band. With the beam position accurately defined by the two end cavities, it should be possible to accurately measure the response of all of the modes to the beam.

A multi-channel system capable of simultaneously measuring all 40 of the TTF2 HOM signals is under consideration. Narrow band filters would be used to select one or two modes (presumably the TE111-6 and TE111-7), and the signals downmixed to an IF of approximately 30 MHz. These signals would be digitized by an array of 12 bit 100Ms/s digitizers (much narrower bandwidth than the 5Gs/s digitizers used in the previous experiment). Extrapolating from the previous results, this system should have a position resolution of 2 microns in each cavity, with a theoretical resolution of < 100 nanometers.

Potential for Multi-Bunch Operation

For a single bunch beam, the relatively narrow (<1MHz) HOM lines are excited by the delta function spectrum of the beam. For multi-bunch beams, the HOM lines will only be excited if a beam harmonic overlaps the HOM mode frequency.

For a 3MHz rate beam, such as the planned TTF2, operation, this is not a serious limitation. In frequency space, the beam spectral lines will overlap (possibly a few line widths away) the HOM lines. It is easy to understand the operation in time. Each bunch will excite the HOM mode. The following bunch, 300 nanoseconds later will add a new vector amplitude to the mode. Due to the reduced integration time (300 nanoseconds, vs. the ~10 microsecond decay time of the mode), the single bunch resolution will be ~5X worse than for the single bunch rate.

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