BEAM POSITION MONITORING USING THE HOM-SIGNALS FROM A DAMPED AND DETUNED ACCELERATING STRUCTURE*

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Abstract

The Next and Global Linear Collider (NLC/GLC) designs require precision alignment of the beam in the accelerator structures to reduce short range wakefields. The moderately damped and detuned structures themselves provide suitable higher order mode (HOM) signals to measure this alignment. The modes in the lowest dipole band, whose frequencies range from 14-16 GHz, provide the strongest signals. To determine the position resolution they provide, an NLC/GLC prototype structure that was installed in the ASSET facility of the SLAC Linac was instrumented to downmix and digitize these signals. The beam position within the structure was determined by simultaneously measuring the signals at three frequencies (14.3, 15, 15.7 GHz) corresponding to modes localized at the beginning, the middle and the end of the 60 cm long structure. A resolution of 1 micron was achieved even with 28 dB signal attenuation, which is better than the 5 micron resolution required for the NLC/GLC.

INTRODUCTION

A charged particle beam loses energy into higher order modes if it passes off-axis through an accelerating structure. The dipole components in particular can spoil the beam quality if not properly controlled. In the case of the NLC/GLC [1], the combination of high frequency (hence small apertures) multi bunch beams and the necessity to preserve tiny beam emittances, made the wakefield control a major challenge. The issue was addressed by designing a damped and detuned accelerator structure which minimizes the long range wakefield (deflection of following bunches) by coupling the HOM power into a manifold through slots in each cell (damping) and by varying the frequency of the deflecting modes (detuning) from cell to cell [2]. However the short range wakefields (distortions within the bunch) can be minimized by keeping the beam centered in the structures. A precision alignment of 5 microns RMS is required for the NLC emittance preservation scheme. Fortunately, the unwanted dipole fields contain information about the beam position. It turns out (see discussion below) that each cell can potentially be used as a beam position monitor (BPM) with an intrinsic resolution in the nanometer scale.

A picture of an NLC/GLC accelerating structure, including HOM couplers built by KEK, is shown in Figure 1. The fundamental mode for this structure is at 11.4 GHz and the first dipole band has a roughly Gaussian distribution between 14 and 16 GHz. To determine the precise location of the electron beam in the structure the HOM signals were measured simultaneously at three frequencies, 14.3, 15.0, and 15.7 GHz, corresponding to mode location at the entrance, middle and exit of the structure. This classical three BPM scheme enables resolution measurements independent from beam position jitter.

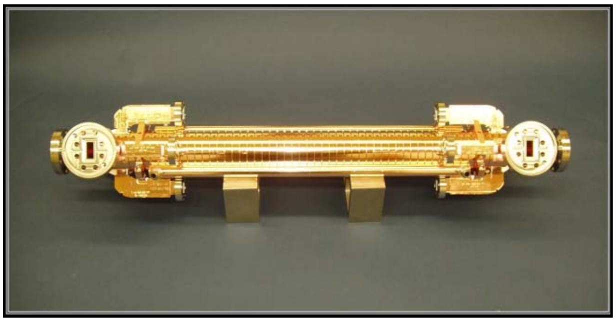

Figure 1: NLC/GLC accelerating structure with power couplers in the horizontal plane and HOM couplers in both planes.

EXPERIMENTAL SET UP

To determine the resolution of such a structure-BPM, a prototype NLC/GLC structure that was installed in the ASSET facility [3] in the SLAC Linac was instrumented to process and record the HOM signals. The beam used for this test consisted of single, 1.19 GeV, bunches of ~2e10 electrons from the damping ring. The bunches were steered in each plane through the ~ 7 mm structure aperture to calibrate the HOM signals. Strip-line BPM's upstream and downstream of the structure were used to measure the beam position in the structure for this purpose. The resolution of these linac BPM's is about 20 microns.

For the structure wakefields to be adequately suppressed, the HOM power has to be well terminated. As a consequence, the HOM signals have to be extracted from the structure through a -20 dB coupler. The broadband HOM signal between 14 and 16 GHz was sent through a triple band pass filter, down converted to 89 MHz using an IQ-demodulator and finally filtered and amplified. The bandwidth of the electronics is 15 MHz. A commercial 8-bit scope was used to digitize the waveforms. The reference for the phase measurement was provided by a simple broad band pickup in the beam line behind the structure. This reference signal was delayed by

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150 ns and then combined with the signal so it could be digitized along with the signal. Figure 2 shows a schematic of the electronics, which were located in the klystron gallery above the linac. The intervening waveguide and cables added about 8 dB of attenuation, so including the coupler loss, the signal was reduced by 28 dB before entering the processing electronics.

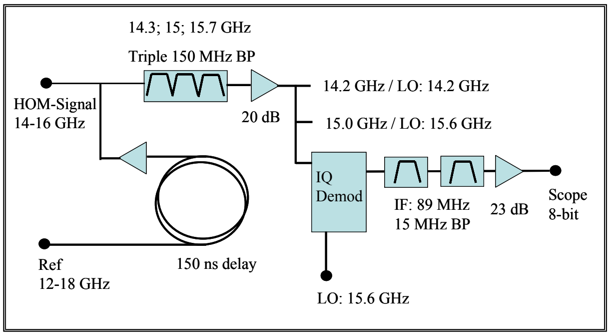

Figure 2: Schematics of the signal processing electronics

RESULTS

The electron beam was centered in both planes by minimizing the signal for the three different frequencies. The beam was steered in one plane correlated with the data taking typically a few hundred microns around the center. The signal strength of the time domain waveform data was determined by fitting the peak in frequency domain. In Figure 3, this Fourier amplitude for the different frequencies is shown as a function of the beam position for a typical data set.

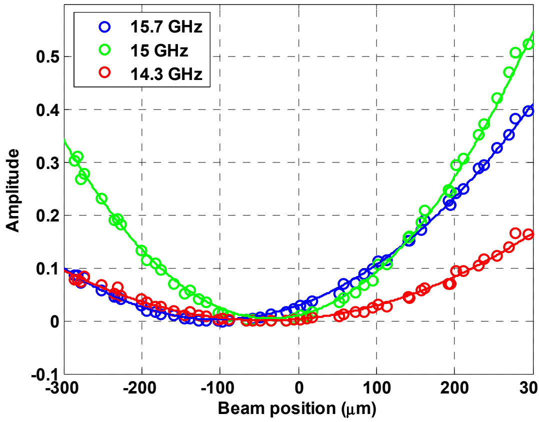

Figure 3: HOM signal power as a function of beam position for the three frequencies.

The phase of the HOM signals was measured relative to the reference phase provided by the broadband pickup. This relative phase as a function of beam position is shown in Figure 4. The data shows impressively how sensitive the phase of the HOM signals indicates the center of the structure, therefore a good phase measurement is essential to achieve a good resolution. The amplitude and phase data was combined to calibrate each BPM (i.e., the signal at each frequency). The beam position is proportional to $A*\sin(\phi-\phi_0)$, where A and ϕ are the amplitude and phase of the signal and ϕ_0 is the midpoint of the phase transition. Using the information from two of the structure BPM's to predict the reading of the third allows the determination of the position resolution independent of the linac BPM data (for this purpose, the resolution of the three structure BPMs were assumed equal). The resolutions determined in this manner are 850 nm in the vertical plane and 1.7 microns in the horizontal plane (the horizontal value is larger due to a higher signal transmission loss). The beam position in the middle of the structure as predicted by the outer two BPM's is compared to the middle BPM reading in Figure 5.

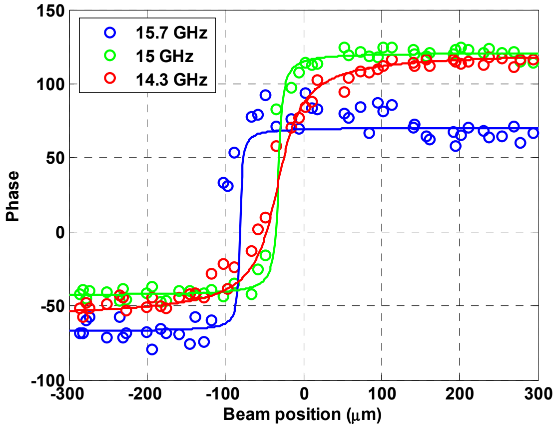

Figure 4: Signal phase as a function of beam position.

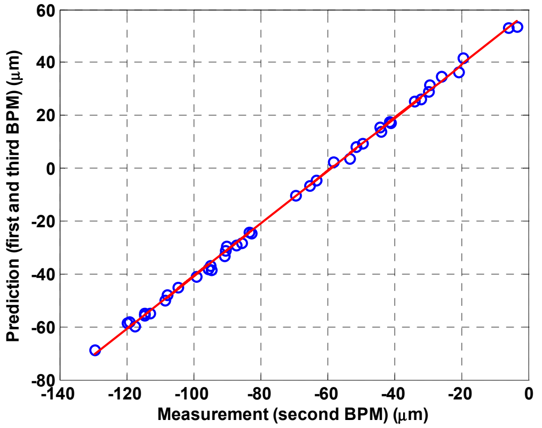

Figure 5: Prediction versus measurement for the middle BPM of the accelerating structure.

The measured data provides also information of the straightness of the accelerating structure and the beam quality. The offset of the predicted versus measured beam position at the center of the structure is a measure of the structure straightness. Using this definition, the structure is straight to about 5 microns horizontally and 25 microns vertically, confirming the precision production techniques developed by SLAC and KEK for these structures [4]. As for beam quality, a close look at the phase plots reveals that the transition is not ultra-sharp at each frequency, which indicates an out-of-phase component in the HOM

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signals [5]. Linear tilts of the electron bunch (i.e. x-z or y-z correlations) will produce such a cosine like component [3]. Thus, the out-of-phase HOM signals can be used as guide to tune the beam.

DISCUSSION

The results presented here are a continuation of work done in the context of NLC [3] and CLIC [6]. Structure BPM resolutions in the 10 µm range have been achieved previously, or were not explicitly measured in such studies. These values are to be compared with dedicated BPM rf cavity experiments that have achieved 25 nm resolution at C-band [5] and X-band [7].

The theoretical resolution of a BPM is determined by the ratio of noise to signal N/S. The thermal noise in a bandwidth B for an impedance Z_0 and electronics with a noise figure N_f is:

$$V_N = \sqrt{4KTBZ_0N_f}$$

For the 15 MHz bandwidth in this case and 50 Ω impedance, 4 µV noise would be measured with perfect electronics. The signal strength for a single cell is described by [8]:

$$V(q,x) = \sqrt{q^2 Z_0 \frac{\beta}{\beta+1} \frac{\omega_0 k_{loss} x^2}{Q_L}}$$

In our case with a bunch charge of q = 2.5 nC, the coupling factor is $\beta >> 1$, $Q_L = 800$ and the loss factor estimated to $k_{loss} = 71$ V/nC/mm^2 we expect a signal strength of 48 mV/µm at 15 GHz [9]. This corresponds to an ultimate theoretical resolution of just below 0.1 nm. The total signal loss accounts to 18 dB (-3dB using only one output port, -20 dB coupler, -8 dB in cable and waveguide, 13 dB net gain in electronics), therefore the expected signal strength reduces to 6 mV/µm. This is somewhat larger than the 3.7 mV/µm value that was measured, which is probably due to additional losses in the structure (some power goes to the upstream ports as well) and uncertainties in the parameter estimates. The lower sensitivity at 14.3 and 15.7 GHz visible in Figure 3 is consistent with the shape of the expected HOM spectrum which has a maximum at 15.3 GHz. The noise level was found to be typically 1.5 mV, considering the 23 dB gain in the final amplifier leads to 106 µV of noise entering the electronics. This is much larger (28 dB) than that estimated assuming only thermal noise sources in the processing electronics, even taking into account the amplifier nose figure of about 6dB.

To improve the resolution the -20 dB coupler could be removed and the electronics could be installed next to the structure. These straight forward changes should bring the resolution down to about 30 nm. Reducing the gain in the electronics and understanding the noise sources better should leave room for even further improvements, enabling a resolution of a few nm. However, systematic effects from the beam shape and cavity distortions are likely to dominate at this level.

CONCLUSION

A single shot BPM resolution of one micron was achieved by using the HOM modes of an X-band accelerating structure. This result comfortably exceeds the requirements for high precision beam based alignment of accelerating structures in NLC/GLC. Consequently the emittance growth from short range wakefields, in normal conducting high frequency linear collider schemes like NLC/GLC or CLIC can be controlled. An earlier test showed that minimizing the HOM signals actually minimizes the short range wakefield as expected [3].

The structure-BPM resolution was limited by electronic noise and the large signal loss between the structure and the processing electronics. The measured signal strength is consistent with theoretical expectations. An optimized setup could result in a resolution of the order of a few nm.

Furthermore the HOM signal provides a measure of the beam quality and can be used as a sensitive diagnostic for beam tuning.

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