Abstract
The Next and the Global Linear Collider (NLC/GLC) designs require precision alignment of the beam in the accelerating structure to reduce short range wakefields. Therefore the moderately damped and detuned structures themselves provide a suitable higher order mode (HOM) signal to measure the beam position in the structure. The required precision for the structure alignment for NLC to minimize the wakefields is 5 microns RMS. This requirement was demonstrated for a NLC prototype accelerating structure using the ASSET facility in the SLAC main linac. The HOM spectrum of the detuned structure ranges from 14 - 16 GHz. The beam position within the structure was determined by simultaneously measuring frequencies (14.3, 15.0, and 15.7 GHz) corresponding to modes localized at the beginning, the middle and the end of a 60 cm long accelerating structure. A resolution of 1 micron was achieved. The resolution was limited by electronic noise.

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 breaking the coherence of the excited spectrum (detuning) from cell to cell [2]. However the short range wakefields (distortions within the bunch) can be minimized by accurate alignment only. A precision alignment of 5 microns RMS is required for the NLC emittance preservation scheme. Fortunately the unwanted higher order 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 at three distinct 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 jitter.

EXPERIMENTAL SET UP
In order to determine the resolution of such a structure-BPM using the HOM signal, a NLC structure was installed into the ASSET facility [3] at SLAC. For this experiment a single electron bunch out of the damping ring at 1.19 GeV was steered in the horizontal and vertical plane to calibrate the HOM signals of the accelerating structure. A number of SLAC standard strip line BPM’s were used to provide a reference trajectory through the structure. The resolution of these BPM’s is about 20 microns. To determine the beam position with very high precision it is essential to measure amplitude and phase for each of the several higher order mode signals. Therefore a down mixing scheme was applied. The primary goal of the test was actually to measure the wakefield of the structure to verify its design. Therefore the HOM power had to be well terminated and the signal for the BPM measurements consequently had to be coupled out 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 150 ns and then combined with the signal to appear on the same
waveform after the signal. Figure 2 shows a schematic of the electronics. The electronics are located in the klystron gallery above the linac adding additional attenuation of about –8 dB after the -20 dB coupler, therefore a total signal loss of -28 dB was estimated before entering the 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: Power of the HOM signal as a function of beam position for the three frequencies.

In order to monitor accurately the phase transition through the electrical center of the structure, the phase of the HOM signals was measured relative to the reference phase provided by the broadband pickup. The 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 (frequency). The signal S is characterized by the following equation $S = A \sin(\phi - \phi_0)$, where $A$ and $\phi$ is the amplitude and phase of the signal corrected by $\phi_0$ determined by the phase transition. The position measurement of each individual BPM is of course limited by the accuracy of the strip line BPM’s providing the position information. Using the information of two of the structure BPM’s to predict the reading of the third allows overcoming this limitation and getting the BPM resolution independent from beam jitter. The resolution of the RF-BPM’s using the HOM modes of an X-band accelerating structure was measured to be just below one micron (850 nm) in the vertical plane and 1.7 microns in the horizontal plane due to a higher loss in the signal transmission. The beam position in the middle of the structure as predicted by the two outer BPM’s compared to the actual reading of the middle BPM is shown in figure 5.

Figure 4: 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 in addition to the beam position. The offset of the residuals can be interpreted as a measure for the straightness of the structure. The structure was found to be straight within 5 microns horizontally and 25 microns vertically confirming the precision production techniques
developed by SLAC and KEK for these structures. A close look at the phase plots reveals that the transition is not ultra-sharp at each frequency, indicating an out of phase component in the rf fields [4]. Tilts in the electron bunch itself or tails from dispersions can produce such a cosine like component. The HOM signal of an accelerating structure consequently provides an operator with an extremely sensitive signal for beam fine tuning.

DISCUSSION

The presented work is a continuation of previous work done in the context of NLC [3] and CLIC [5]. Structure BPM resolutions in the 10 µm range have been achieved previously. This has to be compared to dedicated BPM rf cavity experiments which achieved 25 nm resolution at C-band [4] and X-band [6].

The theoretical resolution of a BPM is determined by the ratio of noise and signal N/S. The thermal noise into an impedance \( Z_0 \) using electronics with a bandwidth \( B \) and a noise figure \( N_f \) is given by:

\[
V_N = \sqrt{4KTBZ_0N_f}
\]

For a bandwidth of 15 MHz into 50 Ω this yields 4 µV for perfect electronics. The signal strength for a single cell is described by [7]:

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

With a bunch charge of \( q = 2.5 \) nC, a strong coupling \( \beta >> 1 \), a \( Q_L = 800 \) and a loss factor estimated to \( k_{loss} = 60 \) V/nC/mm\(^2\), we expect a signal strength of 48 mV/µm at 15 GHz [8]. This corresponds to a theoretical resolution of 0.13 nm. The total signal loss accounts to -18 dB (-3dB using only one output port, -20 dB coupler, -8 dB cable, 13 dB net gain in electronics), therefore the expected signal strength reduces to 6 mV/µm. The measured BPM sensitivity at 15 GHz was 3.7 mV/µm. 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 GHz. The noise level was found to be typically 1.5 mV, considering the 43 dB gain in the electronics attributes 10 µV of noise entering the electronics. One has to assume a very reasonable noise figure of 8 dB to arrive at the theoretical thermal noise level. Removing the -20 dB coupler and installing the electronics next to the structure should provide the potential for a resolution around 30 nm, which is still a factor 230 shy from the above estimated theoretical resolution. The missing factor seems to be comparable to findings of dedicated RF BPM experiments shooting for ultra high resolutions [4, 6].

CONCLUSION

A single shot BPM resolution of one micron was achieved by using the HOM modes of an X-band accelerating structure. The result exceeds comfortably the requirements necessary for high precision beam based alignment of the accelerating structures. Consequently the emittance growth from short range wakefields in normal conducting high frequency linear collider schemes like NLC/GLC or CLIC can be very well controlled. A direct verification demonstrating, that minimizing the HOM signals actually minimizes the residual short range wakefield as well would be still desirable.

The resolution was found to be limited by electronic noise and a large signal loss between the structure and the electronics. The measured signal strength and noise level are consistent with theoretical expectations. An optimized setup should result in a resolution of the order of 30 nm taking into account realistic electronic noise figures.

Furthermore the HOM signal contains many details of the beam quality and can be used as a sensitive diagnostic for beam tuning.

REFERENCES

[8] Z. Li and R. Jones, calculation of the loss factor, private communication