FIRST BEAM TESTS OF A PROTOTYPE BEAM POSITION MONITOR FOR THE CLIC MAIN BEAM*

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Abstract

Beam position monitors (BPMs) throughout the CLIC (Compact Linear Collider) main linac and beam delivery system must routinely operate at 50 nm resolution and be able to make multiple position measurements within a single 156 ns long bunch train. A prototype cavity beam position monitor, designed to demonstrate this performance, has been tested on the probe beamline of CTF3 (the CLIC Test Facility). Sensitivity measurements of the dipole mode position cavity and of the monopole mode reference cavity have been made. The characteristics of signals from short and long bunch trains and the dominant systematic effects have also been studied.

INTRODUCTION

A cavity beam position monitor (BPM) has been installed on the CLIC Test Facility (CTF3) probe beamline, which is described in detail in [1]. It includes a microwave pick-up with two cavities. When the electron beam passes through, it leaves behind electromagnetic fields which oscillate in cavity modes. The position dependent first dipole mode (TM_{110}) is preferentially coupled out of the upstream cavity while the first monopole mode (TM_{010}) in the downstream reference cavity is used to normalise for charge and to provide a reference phase. The modes of interest in both cavities are at 15 GHz.

The signals from each cavity are filtered and then mixed down to an intermediate frequency (IF) with downconverter electronics near the pick-up which also include a gain stage after the downconversion. Currently, the IF is set to about 200 MHz and the signals are digitised with a 2 GS s^{-1} 10-bit digitiser outside the tunnel. More detailed descriptions of the pick-up and installation can be found in [2] and [3] respectively.

A digital down-conversion (DDC) algorithm similar to the one described in [4] is applied to convert the digitised signals to base-band so that the amplitudes and relative phases can be measured. The bandwidth of the digital signal processing is 80 MHz so that the envelope of a short pulse signal is accurately represented. One of the two outputs of the reference cavity has a diode rectifier installed and this is partly used for measurements of the beam arrival time, as is also done in [4]. In this way, the signal amplitude and phase can be sampled consistently.

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CAVITY SENSITIVITY

One of the main goals of the first beam tests was to measure the sensitivity of the monopole reference cavity signal to charge and the sensitivity of the dipole position cavity signal to beam offset. The results are compared with values predicted from the external quality factors Q_{ext}, measured previously [2], and the normalised shunt impedances R/Q, which were calculated for the modes of interest using ACE3P [5] and GdfidL [6]. The theory on which the predictions are based can be found in [7].

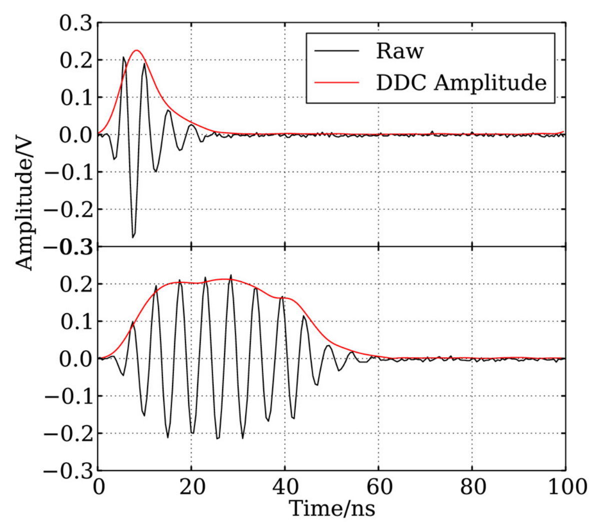

Figure 1: Example of digitised signals from the cavity BPM as excited by a short beam pulse (top) and long beam pulse (bottom) with the amplitude as measured using DDC.

To be able to determine the sensitivity of the pick-up, it is necessary to know the gain of the full system from the cavity output to the digitiser. A signal generator was used in place of the pick-up and the output power from the continuous-wave input was measured using the digitiser. The gains were measured to be -6 dB for the position channels and -17.7 dB for the reference channel. The 3 channels are identical in design but differ in the amount of fixed attenuation at the cavity outputs: 6 dB for the position cavity channels and 20 dB for the reference channel.

Multiple Bunch Excitation

During the reference cavity sensitivity measurement, the charge was measured using an integrating current transformer (ICT). In order to be able to vary the charge easily within the limited dynamic range of the ICT, long beam pulses were used. The sensitivity of the reference cavity

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must be converted from the long pulse response to the single bunch response for two reasons. The first is to be able to compare it directly with the theoretical estimate, which applies to a single bunch excitation. The second reason is so that the reference cavity signal can be used as a charge diagnostic for the position cavity sensitivity measurements. These were performed with a short pulse length of 2.1 ns, which corresponds to 2 or 3 bunches separated by 2/3 ns. This provided the best charge stability while exciting the cavity in a similar way to a single bunch but also meant the charge was too low to be measured using the ICT.

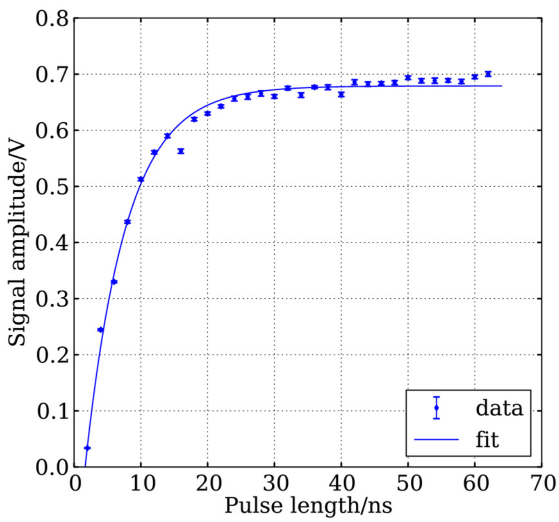

Figure 2: Signal amplitude against beam pulse length for the reference cavity signal.

Examples of raw digitised signals from short and long beam pulses are shown in Fig. 1. The form of the signal excited in the mode of interest by a single bunch passing through a pillbox cavity is a decaying sinusoid. When multiple bunches separated by time t_b pass through the cavity, the signals from each are summed. If all the bunches are of the same charge and in the case of a non axially symmetric mode, have the same offset and tilt, their signals differ only according to their arrival time. The voltage at the arrival of bunch number N is then given by

$$V_{out}(N) = \sum_{n=0}^{N} A_0 e^{-\frac{nt_b}{\tau}} e^{i(n\omega t_b + \phi_0)} \qquad (1)$$

where A_0 and ϕ_0 are the amplitude and phase of the output signal from the single bunch excitation, ω is the resonant cavity mode frequency and τ is the signal decay time. It can be seen that Eq. 1 is the summation of a geometric series where the geometric ratio is given by $e^{i\omega t_b - \frac{t_b}{\tau}}$. Evaluating the summation gives

$$\frac{A}{A_0} = \sqrt{\frac{1 - 2e^{-\frac{Nt_b}{\tau}} \cos(N\omega t_b) + e^{-\frac{2Nt_b}{\tau}}}{1 - 2e^{-\frac{t_b}{\tau}} \cos(\omega t_b) + e^{-\frac{2t_b}{\tau}}}}. \qquad (2)$$

for the ratio of the multiple bunch signal amplitude A to the single bunch signal amplitude A_0. The real exponential factor in Eq. 1 tends to zero with increasing n so the amplitude converges to

$$\lim_{N\to\infty} \frac{A}{A_0} = \frac{1}{\sqrt{1 - 2e^{-\frac{t_b}{\tau}} \cos(\omega t_b) + e^{-\frac{2t_b}{\tau}}}}. \qquad (3)$$

The signal therefore reaches a steady state and is periodic at the bunching frequency. In the case where the cavity resonant frequency is an exact multiple of the bunch arrival frequency, Eq. 2 and Eq. 3 reduce to

$$\frac{A}{A_0} = \frac{1 - e^{-\frac{Nt_b}{\tau}}}{1 - e^{-\frac{t_b}{\tau}}} \qquad (4)$$

$$\lim_{N\to\infty} \frac{A}{A_0} = \frac{1}{1 - e^{-\frac{t_b}{\tau}}} \qquad (5)$$

Eq. 4 tells us that a pulse length of 2.1 ns is short enough since, for decay times as short as 4 ns, the signal amplitude from one bunch will only be 15 % larger than the signal from 3 equally sized bunches of the same total charge, which is the worst case for this pulse length.

The form of the signals from multiple bunches was investigated by varying the pulse length of the laser in the photo-injector. This was done in steps of 2 ns which corresponds to an additional 2 or 3 bunches. The signal amplitude, as determined by the DDC algorithm, was then sampled at its maximum level in the 30 ns after the signal rise. 20 pulses were recorded for each pulse length. The results for the reference cavity signal, which is the most suitable since it is not affected by beam position jitter, are shown in Fig. 2. The rise in amplitude is of the form expected from Eq. 4 which was fitted to the data to obtain a value for the reference signal decay time τ_r. The result is shown in Table 1 along with the decay time from a fit to the tail of the raw signal and the value predicted from the monopole mode bandwidth measured in the lab [2]. The large difference between the three measurements of the decay time suggests that the processing has a large effect on the signal shape.

Table 1: Results of Different Decay time Measurements for the Reference Cavity

Fit data	**Decay time τ_r/ns**
Lab measurement	2.8
Raw signal tail	4.82 ± 0.03
Pulse length scan	6.1 ± 0.2

The frequency of the signals of different pulse lengths was also determined from the phase of the base band signal, as is done in [4]. A data set was used where the signals from the position cavity channels were not so affected by position jitter. The results are shown in Fig. 3. For short pulse excitations, the measured frequency is defined by the geometry of the excited cavity mode and is different for

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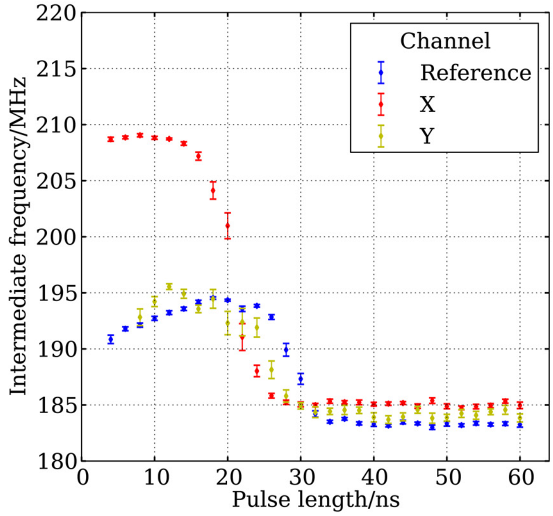

Figure 3: Measured IF against pulse length.

the three channels. However, it is expected from the convergence of Eq. 1 that for long beam pulses, the signals become periodic at the bunching frequency. The dominant frequency is then the same for all three channels and is the nearest harmonic of the bunch arrival frequency.

Reference Cavity Sensitivity

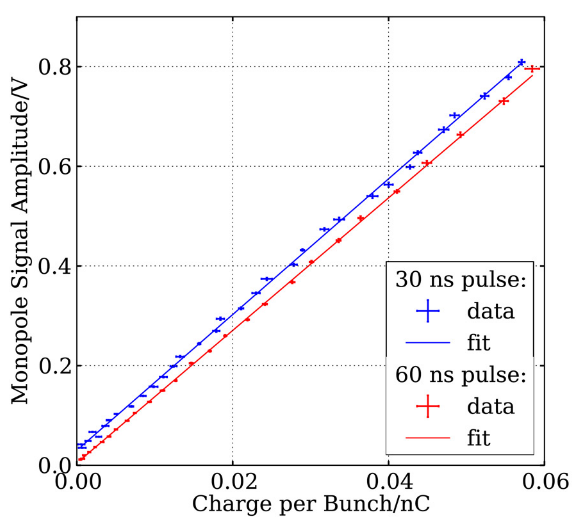

Figure 4: Measured monopole signal amplitude against the charge as measured by the ICT divided by the number of bunches that corresponds to the pulse length.

The reference cavity sensitivity was measured by varying the beam intensity via the attenuation of the photoinjector laser. Successful measurements were made with pulse lengths of 30 ns and 60 ns. For this measurement only, a narrower bandwidth of 45 MHz was used for the digital processing to ensure a clear signal maximum that is still at the steady state level of the multiple bunch signal.

The results are displayed in Fig. 4 and are summarised in Table 2 where the total system gain is accounted for. The

Table 2: Summary of the Results of the Charge Sensitivity Measurement of the Monopole Cavity with the Single Bunch Result Calculated for Two Different Decay Times

Pulse	Sensitivity/V nC^{-1}		
Length/ns	Long train	$\tau_r = 2.8$ ns	$\tau_r = 6.1$ ns
30	623 ± 3	131.9 ± 0.6	64.5 ± 0.3
60	608 ± 2	128.8 ± 0.5	63.0 ± 0.2

results for the two different pulse lengths are close even though they were taken on different days. The systematic offset in the absolute values that can be seen in Fig. 4 does not affect the sensitivity measurement. The single bunch sensitivity has been estimated using Eq. 5 and the decay times in Table 1 that were obtained from the lab measurement and the pulse length scan. The latter includes effects from the processing and gives a result that is far from the estimated sensitivity of 117 V nC^{-1} ($R/Q = 50.6\ \Omega$, $Q_{ext} = 204$) because the addition of the signals from different bunches happens in the cavity before any processing.

Position Cavity Sensitivity

The position cavity sensitivity was measured by varying the beam offset at the location of the BPM over a known range. This was done using a pair of dipole correctors. One of these correctors could be used to vary the beam position and angle or both could be used antagonistically to change the beam position only. The response of the beam to these correctors was measured using the downstream inductive BPMs and screen monitor, both of which feature a calibrated position scale. Since the inductive BPMs are not so sensitive and the screen is a destructive measurement, this had to be done separately from measurements using the cavity BPM. Measurements were made of both the individual correctors as well as their combined effect. For both types of monitor, combining the measured individual corrector responses gives a result that is consistent with the measurement of both correctors together.

The amplitudes of the cavity BPM position channel signals were then measured at different beam offsets with the 2.1 ns pulse length. The time difference between the rise of the diode rectified reference signal and the maximum in the position channel signals was measured beforehand. This was used for the timing so that the position signals were always sampled near the maximum, even when the beam is centred in the cavity and their amplitudes are low. The signal maximum voltage $\hat{V}$ was fitted to the expression $\hat{V}(x) = A|x - B| + C$ where x is the beam offset, and A, B and C are fit parameters. B is the beam offset corresponding to the electrical centre of the cavity and C is the non-zero minimum signal. The signal amplitude is non-zero when the beam is centred because of contributions from the beam tilt and the tails of non-dipole resonant modes. A quadratic fit was also made to the square of the signal maximum, which is proportional to the peak power.

The results of the two fits for both position channels

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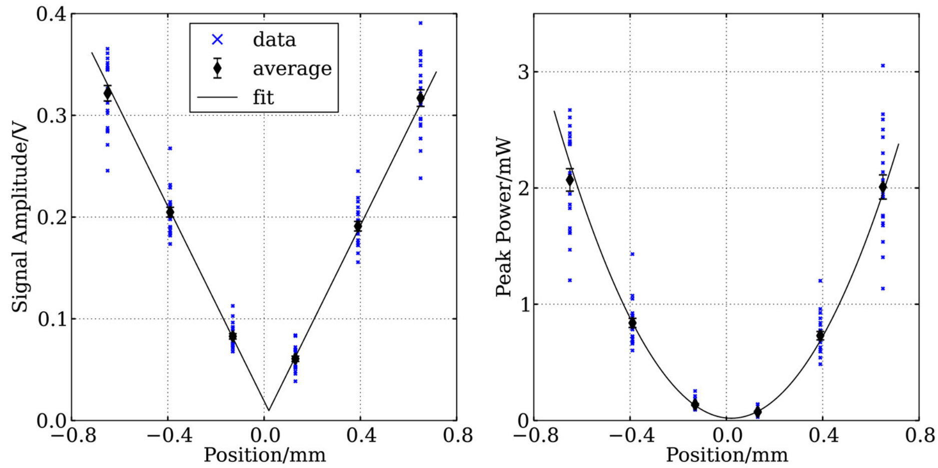

Figure 5: Measured peak signal amplitude and power from the horizontal channel of the position cavity against predicted change in horizontal beam position.

Table 3: Summary of the Results of the Position Sensitivity Measurements of the Dipole Cavity where the Charge Has Been Determined Using the Reference Cavity to Give the Result in $\mathrm{V\,nC^{-1}\,mm^{-1}}$

Direction, Fit	**Sensitivity/ $\mathbf{V\,mm^{-1}}$**	**$\mathbf{V\,nC^{-1}\,mm^{-1}}$**
X, Linear	1.08 ± 0.04	16.6 ± 0.2
X, Quadratic	1.10 ± 0.04	16.75 ± 0.10
Y, Linear	1.04 ± 0.05	15.9 ± 0.4
Y, Quadratic	1.08 ± 0.04	16.6 ± 0.3

are consistent and are summarised in Table 3. The resulting measured sensitivity is close to the theoretical value of 17.1 $\mathrm{V\,nC^{-1}\,mm^{-1}}$ ($R/Q = 3.27\,\Omega\,\mathrm{mm}^{-1}$, $Q_{ext} =$ 615). The charge was measured using the reference cavity for which, the sensitivity measurement was used as a calibration. Fig. 2 was used to convert the calibration to single bunch since the measurement is of short pulses. The conversion factor is the same as for the single bunch sensitivity estimate in Table 2 for the decay time of 6.1 ns.

CONCLUSION

The sensitivity of the reference and position cavities of a cavity BPM have both been measured. The result for the reference cavity had to be converted from the measurement of a long pulse. The 115 MHz bandwidth of the reference cavity is large and the measured decay time is far from the value predicted from lab measurements, suggesting that the signal shape is changed by the processing. An estimate for the single bunch sensitivity, based on the lab measurement, gives 131.9 ± 0.6 $\mathrm{V\,nC^{-1}}$ which is close to the predicted value. A different number based on a pulse length scan, 64.5 ± 0.3 $\mathrm{V\,nC^{-1}}$, is used for short pulse charge measurements. The position cavity has a narrower bandwidth of 66 MHz [2] and so the signal shape should be less affected by the processing. Its measured sensitivity 16.5 $\mathrm{V\,nC^{-1}\,mm^{-1}}$ is close to the predicted value.

If the position cavity sensitivity measurement were repeated with another charge diagnostic or with a high enough bunch intensity so the ICT can measure the short pulse, this would remove the uncertainty associated with the conversion of the reference cavity sensitivity to short pulses. However, increasing the bunch intensity will make the beam position jitter larger which will increase the statistical error. The channels of the cavity BPM will also require attenuation which reduces the signal to noise ratio.

There are other systematics which affect a sensitivity measurement performed in this way. The theoretical model used to predict the sensitivity from the radio-frequency characteristics is based on instantaneous excitation but it is clear from Fig. 1 that the signal maximum does not correspond to the moment where the beam leaves the cavity. Rather, there is a finite signal rise time that is longer than the beam pulse. A comparison of the total energy rather than the peak signal may be better. This can be measured by integrating the processed signals. This method may also prove to be less sensitive to the conversion between short and long pulse excitation.

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