

DEVELOPMENT AND TEST OF HIGH RESOLUTION CAVITY BPMS FOR THE CLIC MAIN BEAM LINAC*

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Abstract

The main beam of the Compact Linear Collider (CLIC) requires the beam trajectory to be measured with 50 nm spatial resolution. It also requires a time resolution capable of making position measurements of the head and tail of the 156 ns long CLIC bunch train, for use in dispersion free steering based on an energy chirp applied along the train. For this purpose, a stainless steel 15 GHz cavity BPM prototype has been manufactured, installed at the CLIC Test Facility (CTF3) and tested with beam. An improved design has been fabricated from copper. We discuss results from the two types of the prototype pickups, both from laboratory tests and from beam tests. We also cover the development of the new downconverter electronics.

INTRODUCTION

CLIC is a proposed next generation linear collider which will have a center of mass energy of 3 TeV. The main linac is 40 km long and the beam delivery system (BDS) is 10 km long in total. Over this distance, a precise, reproducible measurement of the beam trajectory is mandatory with almost 4800 BPMS will be needed to achieve this goal [1]. The BPMS are required to have a spatial resolution of 50 nm and are also required to make multiple measurements along the 156 ns bunch train. This is necessary to distinguish the beam displacement along the energy-chirped bunch train on a dispersive trajectory.

A new system of three prototype copper cavity BPMS have been manufactured and installed in the main beam of the Two Beam Test Stand (TBTS) at the CLIC Test Facility (CTF3). One of these BPMS is shown in Figure 1. The BPMS consist of a cylindrical pillbox position cavity with waveguides which strongly coupled to the two polarisations of the first order dipole mode (TM_{110}). The BPM is also equipped with a reentrant reference cavity, for coupling to the first order monopole mode (TM_{010}). These modes are excited at 15 GHz, as this is a harmonic of the 1.5 GHz bunching frequency allowing signals from each bunch to add constructively and dominate signals from other modes. The chosen harmonic frequency is sufficiently high, to ensure a high shunt impedance, i.e. high position sensitivity, while staying well below the fundamental TM_{01} beampipe cutoff frequency of 29 GHz. The bunch spacing used at CTF3 differs from that proposed for CLIC where the final bunch spacing frequency will be 2 GHz. A cavity with a dipole frequency of 14 GHz is therefore foreseen to be used.

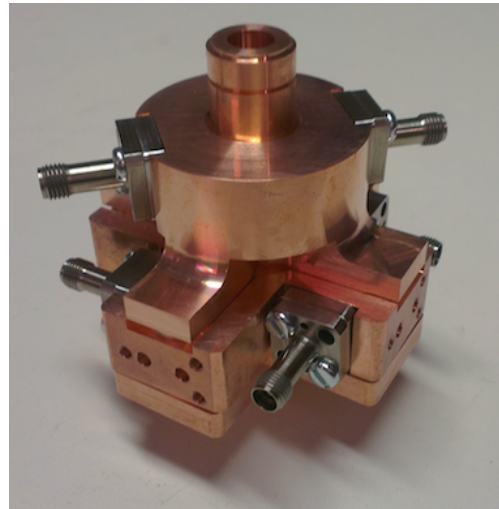


Figure 1: Prototype copper CLIC cavity BPM.

The signal amplitude of the TM_{110} dipole mode, excited in the position cavity by a displaced beam, is directly proportional to beam offset and charge for small offsets [2] while the amplitude of the (TM_{010}) monopole mode is directly proportional to the beam charge, but independent of the beam offset. The (TM_{010}) monopole mode can therefore be used to normalise signals from the position cavity, and used as a phase reference to indicate the sign of the beam position and for rejection of the trajectory and bunch tilt signals.

BPM OVERVIEW

During 2013 and 2014, a stainless steel cavity BPM was tested at CTF3 which performed well, but could benefit from a few improvements [3]. These improvements were taken into account and incorporated into a new design [4]. The old design had a low Q factor of 250, which gave a higher time resolution than required but the position resolution suffered as a result. To improve this, simulations were performed to optimise the Q value. Copper was finally chosen as the material for the new design, to give the best position resolution while maintaining a temporal resolution within the specification. New feedthrough antennas were also designed to remove the necessity of tuning the distance between the antenna and the opposite waveguide wall. The geometry of the reference cavity then had to be slightly modified to compensate the change in resonant frequency and Q value caused by the new feedthroughs. The geometry of the position cavity remained unchanged.

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The manufacture of the copper cavity BPMs proved troublesome, as it took three attempts before the key internal dimensions stayed within our specified tolerances. Parts for five BPMs were manufactured in total, so the pieces for the three BPMs to be installed in CTF3 were selected from the pieces with the most suitable dimensions. Four of the cavity BPMs were brazed and the remaining parts for a fifth pickup were left unbrazed. The best three BPMs, based on the results of bench tests in the laboratory, were selected for installation and the fourth is being used to study the high precision alignment of CLIC quadrupole magnets [5]. Tables 1 and 2 show laboratory measurements of the Q factors and resonant frequencies of the reference and position cavities respectively. The naming of the cavities was arbitrarily chosen during the brazing process.

Table 1: Q Values and Resonant Frequencies of the Copper Reference Cavities after Brazing

BPM	Q_0	Q_{ext}	Q_L	f_0 /GHz
A	1235	2156	790	15.310
B	1133	1851	705	15.182
C	1212	1885	740	15.265
D	1161	1762	705	15.327

Table 2: Q Values, Cross Couplings and Resonant Frequencies of the Copper Position Cavities after Brazing

BPM	Q_0	Q_{ext}	Q_L	Cross-Talk /dB	f_0 /GHz
A	1362	2236	866	-27.0	14.981
B	1338	2341	876	-35.0	14.980
C	1218	2725	866	-40.9	14.987
D	1259	2110	814	-33.9	14.983

From these results it can be seen that the frequency of the reference cavity is on average ~ 300 MHz greater than the expected value of 15 GHz. There is also a large spread in the resonant frequency of the three cavities, indicating that something had been overlooked when redesigning the cavity. Clearly, the frequency is sensitive to something not covered by our specified tolerances and an investigation is underway to look into the cause of this sensitivity. The new feedthrough antennas are a likely candidate as they are very fragile and easily misaligned, with both the Q value and frequency sensitive to this misalignment. However, both laboratory measurements and simulation showed the sensitivity is not high enough to explain the 300 MHz discrepancy. The frequency difference is apparent in the traces shown in Figure 2. The loaded Q factors of both cavities are also greater than the expected value. The temporal resolution of the prototypes is higher than the design value of 50 ns. However, the CLIC specification requires multiple measurements to be made along the 156 ns bunch train, which is still possible with these Q factors. The position cavity central frequencies,

though not exactly at 15 GHz are all closer than the 30 MHz bandwidth of the cavities. The cross-couplings between horizontal and vertical plane are sufficiently low for all BPMs. BPMs B, C and D were chosen to be installed based on these values and the frequency of the position cavities. Cavity C was chosen to be the central BPM as it has the lowest cross-talk and a resonant frequency closest to 15 GHz.

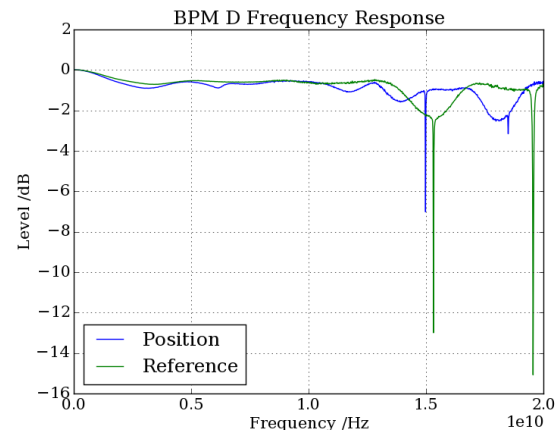


Figure 2: Frequency response of position and reference cavity of BPM D.

SYSTEM OVERVIEW

Originally three copper BPMs were to be installed at CTF3 with three channels on each connected to one electronics module: one for the reference and two for horizontal and vertical measurement. However, the narrow bandwidth of the downconversion scheme and the use of a single Local Oscillator (LO) per electronics module did not allow for simultaneous processing of signals differing by 300 MHz in frequency. The first stainless steel prototype BPM was therefore reused as a suitable reference cavity, and located upstream of the three new copper BPMs. It was then possible to process this with the same electronics module as for the position signals of the copper BPMs with no need for LO frequency alterations. The stainless steel pickup is seen in the front attached to the first copper BPM of the installation shown in Figure 3 with a schematic layout of the new system is shown in Figure 4.

Each of the BPMs is seated on translation stages which move the BPM horizontally and vertically, used for centering the beam. Each of the BPMs is mounted on translation stages which allow the BPM to move both horizontally and vertically, and are used for centering the beam within the BPMs and position calibration. Additionally, there is an optical transition radiation screen downstream of the setup which is useful for steering the beam through the BPMs. The outputs of the BPMs are connected with short coaxial cables to the downconverter electronics which are located in the accelerator tunnel just below the beam line. The LO signal for the mixers and a calibration signal are generated by two RF signal sources upstairs in the klystron gallery. These feed PLL

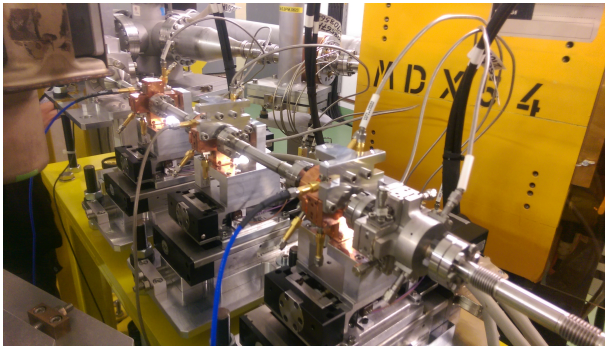


Figure 3: Photo of the new system installed in CTF3.

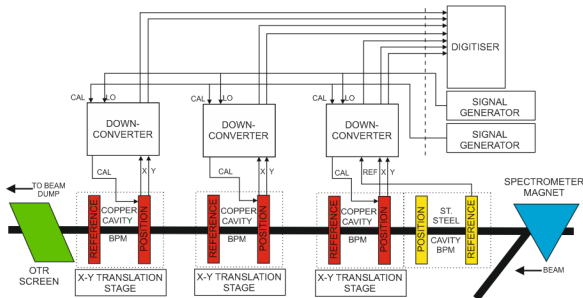


Figure 4: Layout of the new BPM system in CTF3.

controlled RF multipliers (64x) in the electronic modules. The frequency of the LO signal is 235.546875 MHz, which is multiplied by 64 to 15.075 GHz so that 15 GHz signals are downconverted to 75 MHz. A second, gain monitoring signal is derived from 234.375 MHz to give a second 15 GHz signal that can be connected to the unused cavity ports for debugging and online gain monitoring. In the current setup there are 7 electronics outputs delivering the downconverted signals to the gallery, where they are acquired by a set of new 12-bit 250 MS/s digitizers. Ideally, a better resolution digitiser should have been used, but the selected unit was the only suitable card readily supported by CERN's control system.

Downconverter Electronics

There are three downconverter electronic units, designed and manufactured at FermiLab, each with three downconverter boards, one LO board and one calibration signal board. A schematic of one of the downconverter channels with LO and calibration signal is shown in Figure 5.

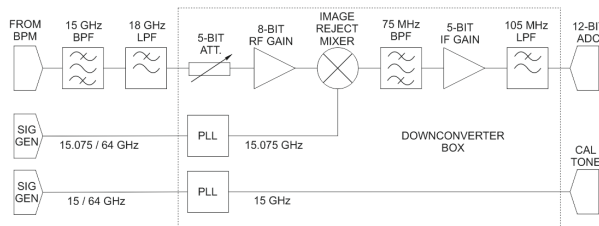


Figure 5: Schematic of one channel of the new downconverter electronics.

The electronics have several improvements over the system used in the previous installation. They include the a 5-bit attenuation and 8-bit gain control in the RF section and a 5-bit gain control in the IF section after downconversion. This provides the user with the ability to optimise the intensity of the analog beam signal throughout the acquisition chain, allowing maximum resolution to be achieved without saturation. The 75 MHz bandpass filter in the IF stage was designed specifically for this system. It has an 18 MHz bandwidth, such that the electronics define the overall bandwidth of the systems and the associated time domain waveform, rather than the individual cavities, which was not the case for the old prototype electronics. The addition of a calibration signal is also useful for remote testing of the electronics without the beam present.

As the variable gain controls were known to be non-linear and to differ between channels, an investigation into the electronics took place where the gains of each of the available nine channels were measured for various gain and attenuation settings. The dynamic range was also measured for one downconverter channel, with various settings. For the calibration of the beam position the overall gain for each individual electronics channel is critical and needs to be precisely measured. The measured gain of each channel is applied to the corresponding signals from the cavity to accurately calculate the actual signal level.

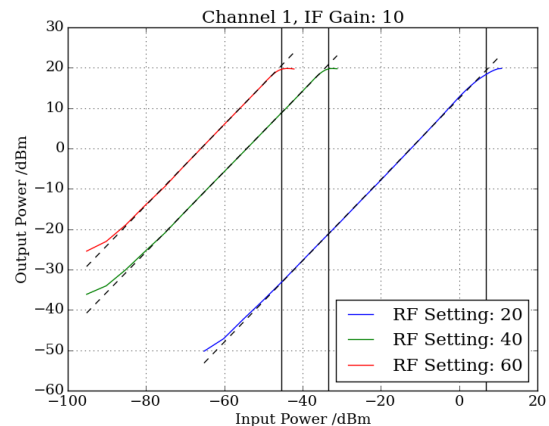


Figure 6: Compression measurements of a single channel of the electronics at various gain settings.

From the investigation, it was observed that increasing the RF gain setting above 60 does not result in any meaningful increase in the measured gain, while when it is set below 10, changing the attenuation setting has little effect on the gain. For the IF gain setting, when it is set to its maximum value of 19, the dynamic range is so small that it is quite unsuitable for beam measurements. From this investigation we decided upon using RF gain settings of 20 to 40 and IF gain settings of 0 to 10. These decisions were also backed up by the measurements of the 1 dB compression points at each setting. Table 3 shows these measurements for one channel and Figure 6 shows a few example curves at differ-

ent gain settings. At higher gains the compression threshold is inherently lower, and so is the range of measurable offsets. A nominal dynamic range of 80 dB is available at the chosen gain settings for initial CTF3 measurements. Future improvements are already foreseen to the system resulting in progress towards higher gains and respectively higher position resolution. This is nevertheless subject to the noise behaviour at different gain settings, which is currently being evaluated.

Table 3: Measured 1-dB Compression Points of a Single Downconverter Channel at Various Gain Settings

RF Gain Setting	0 IF Gain Setting P1dB /dBm	10 IF Gain Setting P1dB /dBm	19 IF Gain Setting P1dB /dBm
20	7.65	7.4	-0.4
30	-7.71	-16.98	-25.83
40	-24.42	-33.47	-42.25
50	-33.19	-41.90	-50.97
60	-36.72	-45.43	-54.34

BEAM TESTS

After the BPMs were installed, the first beam tests began in July. It quickly became apparent that it was difficult to centre the beam horizontally in the first BPM. This was due to the poor initial horizontal alignment. As a result, only the vertical scans taken so far are of interest for resolution and position measurements.

Due to the limited bandwidth of the electronics, the digital downconversion and sampling of the signals had to be modified from the initial method, and as no optimum set of parameters has yet been found to allow resolution measurements. However, the position sensitivity of the copper cavities has been measured. Figure 7 shows an example plot of these sensitivity measurements. The charge sensitivity of the reference cavity has been studied before [3] and the results of this study were used as to normalise the signals for the position sensitivity measurement. These measurements were taken by scanning the translation stages in steps and taking several measurements at each step, normalising and then averaging.

A summary table of the sensitivity values taken from these measurements is shown in Table 4. The sensitivity values were taken calculated using the measured resonant frequencies and Q factors taken from Table 2 and the simulated value for the normalised shunt impedance R/Q (3.27 Ω/mm).

The high external Q of the dipole cavities decreases the potential position sensitivity. Combining these measurements with the gains measured during the lab tests the predicted sensitivities match well with those measured with beam.

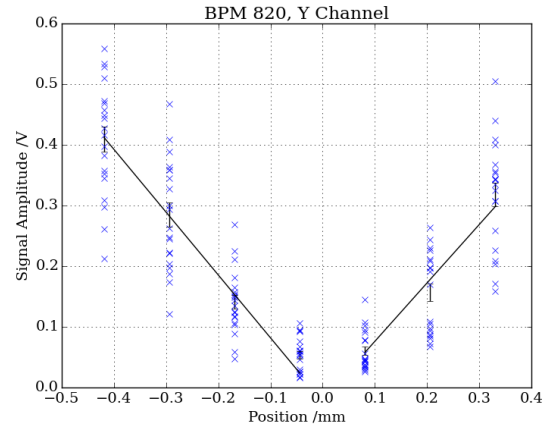


Figure 7: An example of a dipole cavity position sensitivity plot.

Table 4: Summary of Position Sensitivity Values Taken from the Measurements in the Vertical Axis

BPM	Measured Sensitivity $/VnC^{-1}$	Predicted Sensitivity $/VnC^{-1}$
810	8.3 ± 0.5	8.79
820	8.1 ± 0.6	8.16
830	9.5 ± 0.6	9.27

SUMMARY AND OUTLOOK

Redesigned cavity BPMs for possible future use on CLIC are currently being tested at CTF3. The position cavity operates with a resonant frequency and Q factor close to the desired values. However, the reference cavity does not have the desired frequency and there is also a spread of almost 150 MHz in these offset frequencies between BPMs. The cause of this is currently being investigated. The high external Q of the position cavities gives a reduced beam position sensitivity of $\sim 9 /VnC^{-1}$ which has been verified with beam data.

Although initial beam tests have been made with these new BPMs, the main goals are still to be achieved. The first of these goals is to determine the position resolution of these BPMs. The analysis of the current beam data for vertical resolution and then new data needs to be taken for the horizontal position resolutions. Then, ultimately the position resolution and temporal resolution need to be demonstrated simultaneously. To achieve this, an energy chirp will need to be applied to the CALIFES beam at CTF3 and multiple measurements made along the CLIC-like bunch train. Additionally, some consideration needs to be given to the wakefield effects of the cavity. This will be investigated through simulations and comparison with the theoretical analysis.

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