TECHNOLOGIES AND R&D FOR A HIGH RESOLUTION CAVITY BPM FOR THE CLIC MAIN BEAM*

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Abstract

The Main Beam (MB) linac of the Compact Linear Collider (CLIC) requires a beam orbit measurement system with high spatial (50 nm) and high temporal resolution (50 ns) to resolve the beam position within the 156 ns long bunch train, traveling on an energy-chirped, minimum dispersive trajectory. A 15 GHz prototype cavity BPM has been commissioned in the probe beam-line of the CTF3 CLIC Test Facility. We discuss performance and technical details of this prototype installation, including the 15 GHz analogue downconverter, the data acquisition and the control electronics and software. An R&D outlook is given for the next steps, which requires a system of 3 cavity BPMs to investigate the full resolution potential.

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 orbit is mandatory – almost 4800 BPMs will be needed to achieve this goal [1]. The BPMs are required to have a spatial resolution of 50 nm and a temporal resolution of 50 ns, to distinguish the beam displacement along an energy-chirped 156 ns bunch train on a dispersive trajectory.

A prototype cavity BPM has been manufactured and installed in the main beam of the Two Beam Test Stand (TBTS) at CTF3. The BPM consists of a cylindrical pillbox position cavity with waveguides which strongly coupled to the two polarisations of the first order dipole mode (TM_{110}). 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. There, the spacing frequency will be 2 GHz, so a cavity with a dipole frequency of 14 GHz will be used.

The signal amplitude of the TM_{110} mode, excited in the position cavity by a displaced beam, is linearly proportional to beam offset and charge for small offsets. The BPM is also equipped with a reentrant reference cavity, where the first order monopole mode (TM_{010}) is excited at the same 15 GHz frequency. The amplitude of the TM_{010} mode is linearly proportional with beam charge, but independent of beam offset. It is used to normalise signals from the position cavity and as phase reference to indicate the sign of the beam position.

The prototype was manufactured from stainless steel, chosen for its lower conductivity than other common materials for cavity BPMs. This lowers the Q factor, and thus improves the temporal resolution. All signals from both cavities are extracted using vacuum RF coaxial, flange-mount feedthroughs. The 180° rotational symmetry of the pickup means that two ports are available for each of the horizontal, vertical and reference signals. Fig. 1 shows the BPM system installed in TBTS.

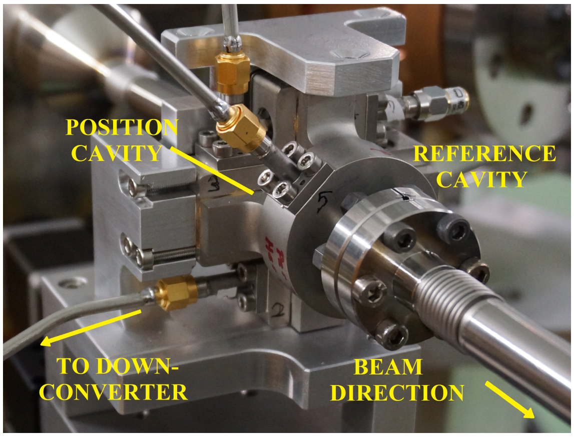

Figure 1: Prototype cavity BPM installed in TBTS.

SYSTEM OVERVIEW AND PERFORMANCE

To extract signals from the BPM a system of electronics is needed in addition to the pickup. Fig. 2 gives an overview of the data acquisition and control components.

The 15 GHz cavity BPM signals are downconverted to a 200 MHz intermediate frequency (IF) by mixing them with a 14.8 GHz CW signal and rejecting unwanted signal frequencies. The 14.8 GHz signal is provided by a local oscillator (LO) assembly, located in the tunnel. The voltage controlled oscillator (VCO), generates the LO frequency, which can be tuned remotely by means of an external DC voltage controlled through a PC running LabVIEW. The downconverter unit also contains step attenuators to scale the dynamic range of the signal processing, they are controlled remotely via a PC interface. The downconverted IF

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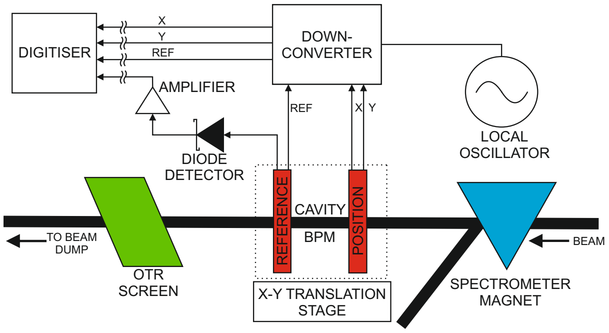

Figure 2: Schematic diagram of the cavity BPM installation in the CTF3 probe beam line.

signals are transferred to a 2 GS/s 10-bit digitiser, located in the klystron gallery, via high quality coaxial cables. The raw waveform data is then available for offline processing and analysis. The digitiser receives the TBTS acquisition trigger, allowing signals to be synchronised with other beam instrumentation in the line (other BPMs, etc.). The downconverter is equipped with three identical channels for horizontal and vertical position and reference cavity signals.

A prototype diode rectifier system was installed alongside the downconverter electronics to provide additional amplitude and timing information from the cavity BPM signals. This system has been attached to the spare output of the reference cavity, utilising a specially designed amplifier. The input impedance of the amplifier was optimised to ensure the 10/90 % rise time of the rectified diode signal met the time resolution.

An optical transition radiation (OTR) screen is installed downstream of the BPM to aid the steering of the beam in the BPM, as well as giving shape and position information of the beam.

The beam position measurement is based on the precise determination of the signal levels of the beam excited horizontally and vertically polarised eigenmodes of the dipole mode resonator, which need to be normalised to the beam intensity by measuring the signal level of the monopole mode in the reference resonator.

Therefore each channel of the downconverter unit was extensively tested before and after installation. Table 1 shows the key characteristics measured in the lab, as well as gain measurements after installation from the downconverter input to the digitiser including insertion losses of cables, etc.

Table 1: Single Downconverter Channel Characteristics

Measurement	Value
3 dB Bandwidth ($\Delta f_{3\mathrm{dB[dc]}}$)	201 MHz
3 dB Frequency Range	14.97-15.18 GHz
Gain - Downconverter Only	+5.0 dB
Gain - D.C. Input to Digitiser	+2.4 dB

To meet the temporal resolution of ∼50 ns, the decay time, τ, of the downconverted signal power was determined. This is essentially set by the loaded Q values, Q_L, of the resonators, as the bandwidth of the downconverter $\Delta f_{3\mathrm{dB[dc]}}$ =200 MHz is larger than the bandwidth of the detected signal $\Delta f_{3\mathrm{dB[cav]}}$ ∼60−120 MHz. Eq. (1) shows the relationship between Q_L, τ and $\Delta f_{3\mathrm{dB}}$ at a given resonant frequency, f_0:

$$Q_L = \frac{f_0}{\Delta f_{3\mathrm{dB}}} = 2\pi\, f_0 \tau \qquad (1)$$

The Q_L's for dipole and monopole mode cavities have been measured in the lab and compared with the beam stimulated measurement of τ. For the position cavity $\tau = 2.1$ ns $\Rightarrow Q_\mathrm{L} = 198$ was measured in the lab, the value calculated during the beam tests was 227. For the reference cavity there was a larger discrepancy, 130 (lab measured), 212 (beam measured). Exciting the cavity BPM with a long beam pulse (>50 ns), it takes about 10 time constants (∼25−30 ns) for the voltage signal to decay to zero (within 1 %) after the stimulus.

The temporal resolution requirement was also met by the diode detector. A 10/90 % rise time of 11 - 12 ns was measured from the diode-amplifier combination. The signal levels recorded at the digitiser are consistent with the design calculations made, and include the measured cable losses. The system is able to resolve beam pulses with charges as low as 25 pC. The system performed well enough to warrant a system of three diodes and amplifiers based on the prototype.

PROTOTYPE SYSTEM REDESIGN

The first run of beam tests has been performed with prototypes of the cavity BPM and the 15 GHz downconverter electronics, as well as a commercial PCI digitiser for the data acquisition at CTF [2]. Although the performance of the prototype was promising, we found several points in all areas, cavity BPM pickup, downconverter and DAQ, where this system can be improved substantially.

Position Cavity

One such point is the Q factor of the position cavity. The overall or loaded Q factor, Q_L, of a resonator is determined by the internal Q factor of the resonator itself, Q_0, and by an equivalent external Q, Q_ext, caused by the loading effects when coupling to the external network. Eq. (2) gives the relationship between these three values [3].

$$\frac{1}{Q_\mathrm{L}} = \frac{1}{Q_\mathrm{ext}} + \frac{1}{Q_0} \qquad (2)$$

The Q factor of the cavity can be optimised for highest resolution. From that perspective, Q_0 should be as high as possible, minimising the internal losses and therefore unnecessary wastage of the beam energy. When Q_ext is high, the energy coupled from multiple bunches add up within the cavity, but only a fraction of it is extracted into the external network. In turn, a very low Q_ext means that most of the energy is extracted from the cavity before signals from multiple bunches can add up, hence, there is little or no gain due to multiplication. This suggests that there is an optimum value for Q_{ext}. Simplistic simulations suggest that for CTF3 probe beam parameters, using copper as the material with other aspects of the cavity design unchanged, the optimal Q_{ext} is around 500 (Fig. 3), which still allows for a 50 ns temporal resolution. Simulating a copper cavity in CST Microwave Studio (MWS) and ACE3P yielded a Q_{L} of 517 and 525 respectively. These values correspond to voltage signals that take just over the required time to decay to >1 %, 50.5$-$51.3 ns. However, the simulations do not take into account the surface roughness of the material, which will inevitably lower the Q_{L} below the goal. Further simulations should demonstrate the combined spatial and temporal resolutions required for dispersion measurements in CLIC.

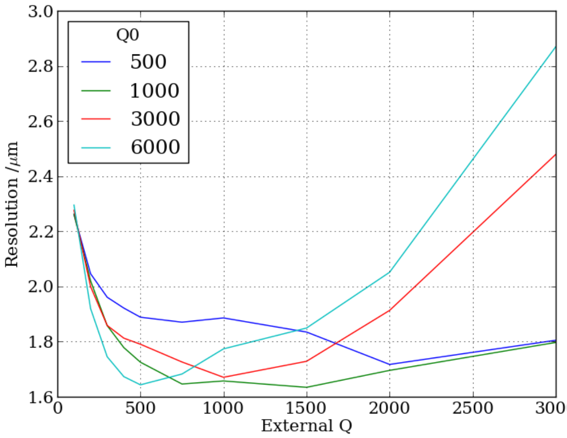

Figure 3: Results of optimisation simulations using BPMs with various Q factors.

Another issue that needed to be improved was the tolerances on the waveguide to coaxial transition of the position cavity. The transition, shown on the left of Fig. 4, is simply a feedthrough mounted on the side of the waveguide with the inner antenna extending into the waveguide close to the opposite wall.

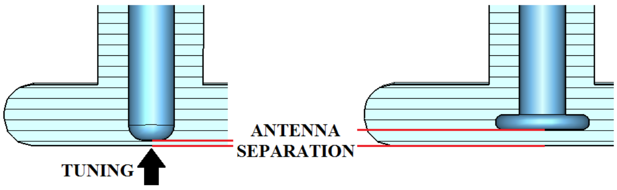

Figure 4: Waveguide to coaxial transition in the current prototype (left) and the new design with a bead on the antenna tip (right).

The external coupling from the waveguide is very sensitive to the separation between the feedthrough antenna and the wall. The strongest coupling is achieved when this separation is small: 0.169 mm in simulation and 0.1 mm in lab measurement [4]. This small distance causes capacitive coupling between the waveguide and antenna, explaining the sensitivity to this separation. To compensate this sensitivity, the prototype features tuning mechanisms. These tuners push against the waveguide wall, allowing the control of the separation to optimise the coupling. The need for these tuners can be removed by reducing the sensitivity to separation. MWS was used to simulate this transition. The return loss from the waveguide port was calculated while the separation was altered. As a way of quantifying the sensitivity to this distance, the range of separation where the return loss was kept below -30 dB at 15 GHz was recorded. For the prototype design, this range was 29 μm. Fig. 5 shows examples of return losses for different separations which are below -30 dB at 15 GHz.

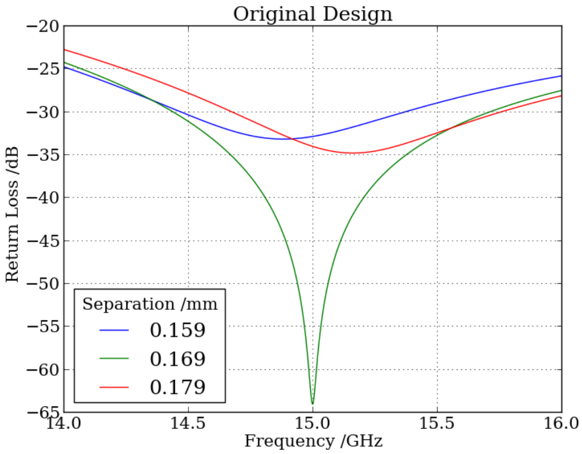

Figure 5: Return losses of the current waveguide to coaxial transition for three different antenna separations.

New feedthroughs will be used in future BPMs to provide stronger coupling. They have different dimensions and will feature a threaded antenna, allowing it to be changed with an alternative design. When these new dimensions were simulated the sensitivity to separation was still high. An investigation into a new feedthrough antenna was made, where several designs were simulated. The most promising of which was an antenna with a bead on the tip. In simulation, the beaded design gives a separation range of 63 μm, with a larger optimum separation of 0.516 mm. Fig. 4 shows the new antenna design in comparison with that used in the current prototype.

With the new feedthrough antenna design the simulated Q_{L} of a copper cavity is virtually unchanged at 524. A summary of the measured [5] and simulated Q_{L}'s of the position cavity are shown in Table 2.

Reference Cavity

The new dimensions of the feedthroughs in the reentrant reference cavity cause f_0 to increase. When simulating the

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Table 2: Simulated and Laboratory Measured Loaded Q Factors at Different Stages in the Position Cavity Design

Geometry	MWS Q_L	ACE3P Q_L	Lab Q_L
Prototype	268	293	198
Copper Cavity	517	525	-
Copper w/ Bead	-	524	-

cavity, although the calculated f_0 is lower than the measured value, the increase seen was similar in MWS and ACE3P, 16 MHz and 20 MHz respectively. The dimensions of the reference cavity needed to be altered to compensate this change and also to match the Q_{L} of the cavity to that of the position cavity. Previously it had been 130, lower than the value from the position cavity of 198. Through simulation, the cavity geometry was altered to restore f_0 close to the original value. Increasing the separation between the feedthrough antenna and the opposite wall of the reentrant part increases the Q_{L} with little effect on f_0, allowing the Q_{L} of the cavity to match the position cavity. A cross section of the reference cavity with new dimensions is shown in Fig. 6. Table 3 shows the measured and simulated f_0's and Q_{L}'s.

Table 3: Simulated Resonant Frequencies and Loaded Q Factors at Different Stages in the Reference Cavity Design

Geometry, Code	f_0/GHz	Q_L
St. Steel Prototype, Lab Measurement	15.012	130
St. Steel Prototype, MWS	14.941	149
St. Steel Prototype, ACE3P	14.938	149
Copper w/ New Feedthrough, MWS	14.957	245
Copper w/ New Feedthrough, ACE3P	14.958	247
New Cavity Dimensions, MWS	14.938	527
New Cavity Dimensions, ACE3P	14.939	497

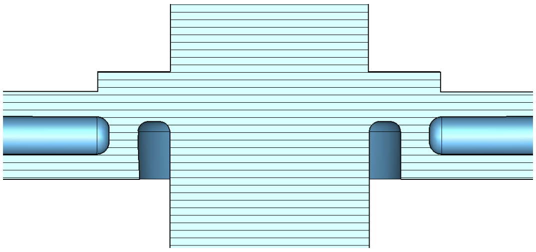

Figure 6: Cross-section of reference cavity with new dimensions and feedthroughs.

Electronics

In addition to improvements on the cavity BPM pickup, a physical compact RF downconversion electronics system is being investigated. This new downconverter will have nine identical channels to process X, Y and REF signals from three cavity BPMs. Rather than individual connected components, it will likely be in the form of a PCB. The IF will be in the range 70−100 MHz, and with a smaller IF bandwidth. In this way the waveforms are defined by the IF filter, not by the cavity resonances, thus providing very similar waveforms for position and reference signals to be digitised. In addition to the LO VCO the system will also be equipped with a calibration signal VCO. This CAL signal can be split and fed into the unused, symmetric ports of the BPM, and may provide a loop-thru system check at times when no beam is present. Other features will include remote sensing of signal levels, supply voltages, temperatures, etc. A higher resolution 14-bit, 250 MS/s digitiser with 70 dB dynamic range is foreseen to demonstrate the spatial resolution. The lower sampling rate allows an IF of up to 100 MHz to be digitised in the 1st Nyquist passband. As the required system bandwidth is 30 MHz, this lower IF should cause no performance limitation. The layout of the proposed downconverter electronics is show in Fig. 7.

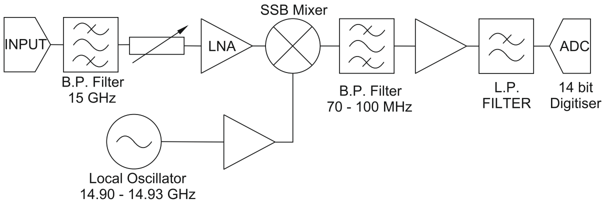

Figure 7: Diagram of a single channel of the proposed downconverter electronics.

OUTLOOK

The next beam tests of the BPM will take place in the autumn with some modifications to the system. These include translation stages to control the beam position inside the pickup, a system of three diode rectifiers and magnification in the OTR system. Dimensions of the redesigned prototype BPM have been finalised and passed on to a designer. If it is feasible to construct such a design from copper then the manufacturing process can begin. As with the current prototype, the new pickup will have to be extensively tested.

In the longer term, the goal is to have a system of three BPMs installed in CTF3, along with a dedicated electronics system. This will allow a determination of their spatial resolution. Ultimately, the combined spatial and temporal resolution required for CLIC needs to be demonstrated by introducing position modulation into the beam at CTF3.

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