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DEVELOPMENT OF A CAVITY BEAM POSITION MONITOR FOR CLIC*

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Abstract

The Compact Linear Collider (CLIC) project presents many challenges to its subsystems and the beam diagnostics in particular must perform beyond current limitations. The requirements for the CLIC main beam position monitors foresee a spacial resolution of 50 nm while delivering a 50 ns temporal resolution within the bunch train. We discuss the design of the microwave cavity pick-up and associated electronics, bench top tests with the first prototype cavity, as well as some of the machine-specific integration and operational issues.

INTRODUCTION

The CLIC design for 3 TeV centre of mass energy includes a 40 km long main linac and a 10 km long beam delivery system (BDS) which require precise beam position monitoring for operation. This will be achieved using close to 4800 cavity beam position monitors (BPMs), one for each of the 4196 quadrupole magnets in the main linac and a further 600 in the BDS. These must have a small spatial resolution of 50 nm and a time resolution of 50 ns in order to provide multiple, accurate position measurements within a single bunch train. They must also operate in an environment where large shifts in temperature are expected [1].

A prototype cavity BPM has been designed and built to be tested on the CLIC Test Facility 3 (CTF3) probe beam later this year. It consists of two cavities, a position cavity and a reference cavity. The position cavity is a cylindrical pillbox with rectangular waveguides that strongly couple to the first resonant dipole mode in two polarisations (TM_{110}). The amplitude of each polarisation is proportional to the beam offset in one transverse dimension. The dipole mode frequency of 14.99 GHz is close to 14 GHz which will be used for CLIC. It was chosen so that signals from consecutive bunches, separated by 0.667 ns (0.5 ns for CLIC), add constructively and dominate signals from other modes excited by the beam. The reference cavity is re-entrant and its first monopole mode (TM_{010}) is used for bunch charge normalisation and a reference phase. It has the same frequency as the position cavity first dipole mode so that the same processing can be applied to both for improved stability. Both cavities are designed to have low quality factors so that the signal from any one bunch has decayed by a factor of order 1000 within the time resolution. The beam pipe through the assembly has the same 4 mm radius as the CLIC main linac.

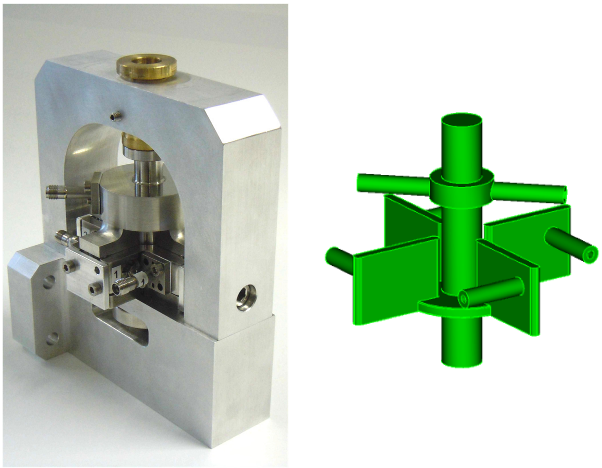

Figure 1: The prototype pick-up assembled in a clamp specifically designed for the bench measurements (left) and the vacuum geometry (right).

A photograph of the two cavity assembly, which consists of four parts made from stainless steel, is shown in Fig. 1. The signals are extracted via feedthrough antennas in the re-entrant part of the reference cavity and at the end of the waveguides in the case of the position cavity [2].

DIPOLE MODE MEASUREMENTS

Table 1: Quality Factors and Resonant Frequency f_0 of the Position Cavity Dipole Mode, Both Measured and Predicted from Simulation

Parameter	measured	predicted
f_0/GHz	14.993	14.990
Q_L	224	274
Q_{ext}	830	700
Q_0	306	450

Before the assembly was brazed, the quality factors of the first dipole mode of the position cavity were determined from the transmission from a single weakly coupled antenna positioned in the beampipe, to each output port of the BPM in turn. The remaining ports were either short circuited or terminated with matched loads. In the case where the other ports are terminated, the measured loaded quality

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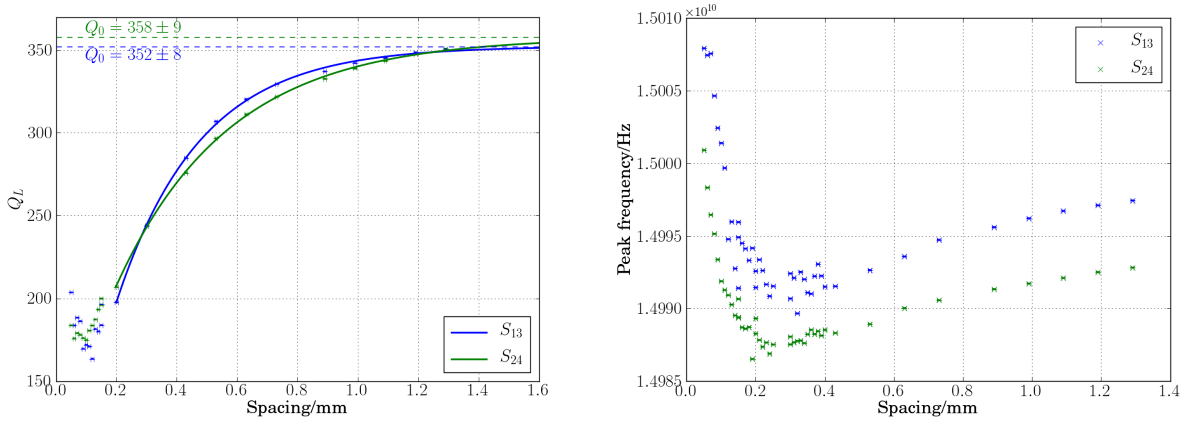

Figure 2: Quality factor (left) and resonant frequency (right) of the position cavity dipole mode as the feedthrough-waveguide spacing was varied.

factor Q_L can be obtained from

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{ext}} \tag{1}$$

where Q_0 and Q_{ext} are the internal and external quality factors respectively. In the case where the other ports are shorted, the measured quality factor $Q_{L,shorts}$ depends on the mode orientation but must lie between two extremes:

$$\frac{1}{Q_{L,shorts}} = \frac{1}{Q_0} + \frac{1}{2Q_{ext}} \tag{2}$$

in the case of maximum coupling between the dipole mode and the port being measured and

$$\frac{1}{Q_{L,shorts}} = \frac{1}{Q_0} \tag{3}$$

in the case of no coupling at all. The median of these two values was taken and used to calculate Q_{ext} and thus, Q_0. The results are summarised in Table 1 along with what was predicted from simulation. The discrepancy between the measured and predicted values can be attributed to the surface roughness and the non-ideal electrical contacts of the BPM assembly.

The sensitivity of the coupling to the positions of the feedthrough antennas was high in simulation [2] and so this was also measured. Shims of 0.48, 0.23, and 0.10 mm were used to vary the separation between the end of each feedthrough antenna and the wall of the corresponding waveguide. This had an effect on the resonant frequency and the quality factor and these were measured from the transmission between opposing BPM ports. The results are shown in Fig 2. The measured loaded quality factor tends to the internal quality factor as the coupling decreases [3]. Therefore, an increasing exponential curve was fitted to the results in order to obtain an estimate for Q_0 of 356 which is significantly higher than the measured value in Table 1. The effect was also studied with higher resolution using shims made from 0.01 mm thick aluminium foil. These points are not included in the fit because they are too inaccurate. However, they show that the maximum cavity coupling is achieved with a spacing of about 0.1 mm, which differs from the design separation of 0.177 mm. Simulations in Omega3p, an eigenmode solver from the ACE3P suite of radio frequency simulation codes [4] suggest this may be due to coupled low Q resonances trapped in the waveguides that are tuned to 15 GHz at this separation and thus, reduce the external quality factor below its design value.

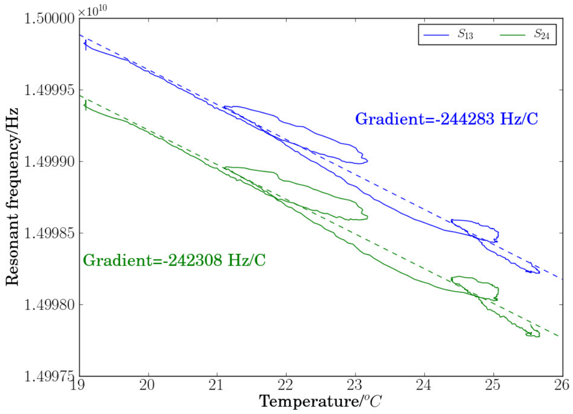

Figure 3: Variation of the resonant frequency of the dipole mode with temperature.

The variation of the resonant dipole mode frequency with temperature was also investigated. The setup was left over one weekend, over which, two clear fluctuations in the ambient temperature and a net change of -6 °C were observed. The resonant frequency was determined from the peak port to port transmission and a temperature stability of 243 kHz·°C^{-1} was observed as shown in Fig. 3. The maximum 20 °C temperature shift expected during CLIC operation therefore corresponds to a change in frequency of about 5 MHz. How this affects the phase stability of the BPM depends on how the frequency of this

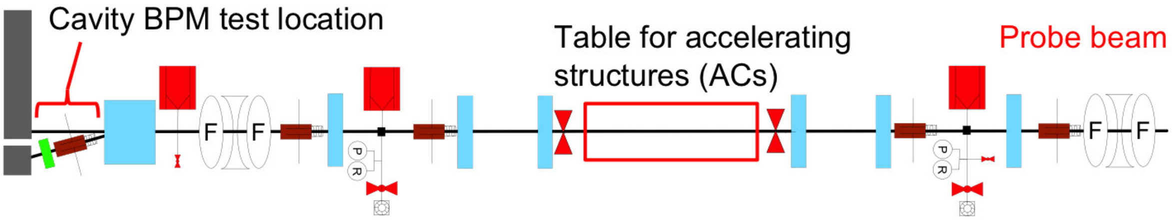

Figure 4: Beam line diagram of the probe beam in the CLIC experimental area (CLEX) with the cavity BPM test location indicated [5].

mode changes relative to the monopole mode in the reference cavity, whose temperature stability also needs to be measured. The hysteresis from the heating and cooling of the cavity material during the two temperature fluctuations is clearly visible. A probe attached to the pick-up itself would provide a more accurate measurement.

The effect of the cavity temperature was also simulated. The mesh was scaled according to the thermal expansivity of stainless steel (16.5×10^{-6} °C^{-1}) and solved again for the resonant frequencies. The results for the reference and position cavities were both 247 kHz·°C^{-1} which is close to the measured temperature stability of the position cavity and equal to the expansivity multiplied by the resonant frequency as might be assumed.

REFERENCE CAVITY MEASUREMENTS

Due to an error in communication, the resonant frequency of the built reference cavity was higher than its design value. For this reason, the reference cavity was modified by increasing its diameter by 0.98 mm. The results of measurements taken before and after the modification are shown in Table 2. An increase of the resonant frequency of about 33 MHz and an increase in the loaded quality factor by a factor of about 2 is expected when the feedthroughs are correctly positioned after brazing.

Table 2: Measurements of the Reference Cavity Monopole Mode Before and After Modification

Parameter	**original**	**after modification**
f_0/GHz	16,940	14.960
Q_L	153	74
Q_{ext}	276	-
Q_0	343	-

OUTLOOK

The cavity is now brazed and vacuum tight. The feedthroughs must be fixed in place with silver plated copper gaskets before another vacuum test. After this, a second round of RF measurements can be made.

The down-mixing electronics used for the first beam tests will consist of field-replaceable connectorised components and will down-convert the signal from the pick-up to an intermediate frequency of around 100 MHz. The specification of the digitisers will initially be constrained by availability although it is desirable to maintain a large bandwidth throughout the processing so the rise time of the multibunch signal doesn't degrade the time resolution.

The prototype BPM will be installed at the end of the probe beamline at CTF3 as shown in Fig. 4. This location was chosen as there are space limitations in the rest of the beamline, the quadrupole triplet just upstream will allow some control of the beam focusing and the small BPM aperture will not interfere with future tests of accelerating structures in the location indicated. A test stand must be designed and installed since the section of beamline chosen is not supported by a girder and at present, lacks a beam pipe. A mover will also be required for calibration.

The first tests will focus on signal processing, sensitivity and time resolution. The probe beam linac (CALIFES) can provide a single bunch of 0.6 nC as well as a train of up to 150 smaller bunches separated by multiples of 0.667 ns at a repetition rate of 5 Hz. This will allow the effects of bunch charge and spacing to be studied in detail. The main challenge for the signal processing will be to deal with the signals from previous bunches so that the desired time resolution can be achieved. Two or three more prototype cavities, with some possible redesign depending on the results of beam tests at CLEX, are envisioned. This will allow a test of BPM spatial resolution and analogue bandwidth.

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