Aims and initial progress of TPMON task

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Abstract

TPMON is part of EUROTeV’s Work Package 5 that covers diagnostics. The aim of the task will be to investigate the feasibility of a precision bunch train timing measurement at 30 GHz, aiming for an accuracy of 10 fs. Tests of the electronics will be carried out at CERN’s CTF3. Initial work is concentrating on studying the optimum method of intermediate frequency phase detection.
1 Introduction

The Compact Linear Collider (CLIC) \cite{1} requires a very tight tolerance on the timing jitter between main and drive beams \cite{2}. Errors lead to energy variations in the main linac and a subsequent reduction of luminosity. It is extremely doubtful that the required tolerance could be met without some form of beam-based correction and one system that appears promising is a feedforward compensation. The drive beam phase is measured before, and then corrected after, each drive beam turn-around. Correction would be done using RF structures, either with deflecting cavities or by varying the energy before the final bunch compressor.

Although optical fibre phase distribution systems are starting to achieve the required level of stability (albeit for relatively short links), an alternative scheme for CLIC that would appear to be very attractive would be to use the beam in the outgoing transfer line of the main linac as the timing reference (Fig. 1). This way, errors of the main beam phase with respect to the master RF oscillator will also be taken into account and compensated. As the arrivals of the main beam and drive beam trains do not coincide, a precision local clock is required to keep time from the arrival of the outgoing main beam to that of the corresponding drive beam, a maximum of 92 µs later. Clocks that give an error of less than 10 fs over this time are available. In addition to this requirement, a precision beam timing measurement is vital to the scheme and achieving this with the required accuracy has yet to be demonstrated. A natural choice would be to perform this measurement at 30 GHz and the principle goal of the TPMON task will be to show its practicability.

Fig. 1 Use of the outgoing main beam transfer line as phase reference.
2 Scope of TPMON task

The objective of the task will be to build the electronics for a high precision RF-based bunch timing measurement system. The phase of a bunch train will be measured at 30 GHz with the aim to approach an accuracy of 10 fs for a single-shot wideband measurement. A bandwidth in the region of ±50 MHz would be required. This would permit intra-pulse compensation within the 70 ns drive beam train up to the bandwidth of the CLIC accelerating structures. An essential part of the work will consist of testing in an accelerator and it is envisaged to do this in CTF3 [3].

A simplified block diagram of the proposed set-up is shown in Fig. 2. Although purpose built RF structures will be required for any final system, it is not likely that they will introduce any performance limitation and hence their development will not be a priority. For tests in CTF3, a 30 GHz PETS [4] structure can be used. As the beam jitter will be much greater than the system's resolution, two systems will be made and their outputs compared. Clearly, this test does not include the jitter introduced by the RF reference source that is common to both systems. As microwave sources with an acceptably low jitter are available commercially, the use of independent oscillators is not likely to be a feasibility issue and will not be included in the system to begin with.

![Fig. 2 Set-up for measurements in CTF3](image-url)

A major part of this work will be studying the best method of intermediate frequency (IF) phase detection, in particular optimizing performance in the presence of amplitude variations. Initial work is concentrating on this area.
3 Phase detection

3.1 Tentative requirements

- single shot
- ± 50 MHz bandwidth
- < 0.1 degree resolution (equivalent to 9 fs at 30 GHz)
- ± 5 degree range
- > 6 dB amplitude range

3.2 Options

Today, phase detection is commonly achieved digitally after analogue to digital conversion of the IF signal. Unfortunately the combination of phase resolution and bandwidth rule out this option with ADC's available at present. Alternatives include analogue mixers and analogue multipliers. Analogue mixers have the necessary bandwidth and resolution but generally have a large amplitude dependence that would make them impractical for a high precision measurement. Analogue multipliers generally behave better in this respect but tend to be more noisy.

One possible option may be to use of an array of analogue multipliers (Fig. 3), summing their outputs to increase the signal to noise ratio. This signal is then sampled and a correction could then be applied for amplitude dependence.

In any case, a careful characterization of available devices is required to find the most suitable solution. This work is presently being carried out and is described in Section 3.3.

![Fig. 3 Possible phase detection scheme.](image)
3.3 Characterization of IF phase measurement devices

Let us consider the problem of detecting the phase between two signals:

\[ V_1(t) = A(t) \sin(\omega t + \phi(t)) \]
\[ V_2(t) = \cos \omega t \]

An ideal multiplier or mixer would produce the output:

\[ V_{\phi} = \frac{A(t)}{2} \sin(2\omega t + \phi(t)) + \frac{A(t)}{2} \sin \phi(t) \]

Assuming \( \phi(t) \) and \( A(t) \) vary slowly compared to \( \sin \omega t \), we have an easily isolated low frequency component proportional to the input amplitude and to the sine of the phase, or the phase directly at small angles. An actual phase detector will of course deviate from this ideal behaviour. In particular we find a more complicated amplitude dependence. We must thus establish that the input phase can be recovered with sufficient accuracy over the desired amplitude and phase ranges, taking into account both non-linearities and noise.

Fig. 4 Test setup block diagram.
3.3.1 Test setup

An automated test setup (Fig. 4) has been built and the first tests have been performed. The IQ modulators have a well behaved linear phase response. When changing amplitude a phase shift is however also introduced. We must thus make an accurate narrow-band phase measurement of the IQ modulator outputs in order to relate phase measurements at different amplitude levels to each other. Having thus established the narrow-band behaviour of our phase detectors and amplitude detectors we can drive one of the IQ modulators with a high frequency phase modulating signal to obtain the frequency response of the devices under test. The current setup can only measure narrow-band phase with about a 0.1° resolution. The data are thus only preliminary as a more precise narrow-band phase measurement will be required to obtain an accurate amplitude correction. The motivation of these first tests is primarily to establish that we have at least one device that will work at the selected IF. Fine-tuning the calibration of the devices will have to be done when better narrow-band phase measurement equipment has been obtained.

3.3.2 Obtained Data

Two phase detectors have been tested so far. One is an analogue multiplier, Analog Devices AD835, the other a double balanced mixer, Mini-Circuit ZFSC-2-2. The amplitude detector used was the Analog Devices AD8318. The outputs of the phase detector $V_\phi$ and of the amplitude detector $V_A$ are fitted to the input phase using a polynomial of third order in $V_A$ and first order in $V_\phi$.

$$\phi = a_{0,0} + a_{0,1} V_\phi + a_{1,0} V_A + a_{1,1} V_A V_\phi + \ldots$$

Fig. 5 and Fig. 6 show the errors between input phase, and phase computed from the outputs of the phase detector and the amplitude detector. The first plot in each figure shows the error in a fit at each amplitude level to the input phase. The second plot shows the error of the full phase/amplitude fit. Since our input phase, as measured by a vector voltmeter, is only known to 0.1°, we obtain a surprisingly good fit over the amplitude range. This gives some confidence that with a better input phase measurement a sufficiently close correspondence will be possible. For the AD835 the frequency response (Fig. 7) was also obtained at power levels over a 7 dB range and indicates that the multiplier configuration is well behaved to 50 MHz. Noise measurements (Fig. 8) show that as we increase the number of multipliers from one to two and sum their outputs the total noise decreases by about a factor of $\sqrt{2}$ as expected, taking into account only the phase detector noise. When we include the amplitude detector noise we notice that the decrease is less as only the phase detector is currently averaged. The amplitude detector noise has more of an impact towards the extremes of the amplitude range as its effects are amplified by the third order polynomial fit of the amplitude correction. The two devices were tested at 250 MHz and 750 MHz and work about equally well at these two frequencies. These two frequencies were chosen for comparison as they are available in the CTF3 frequency generation electronics and a choice of either would facilitate later tests of the complete system with beam.
Fig. 5 Mixer errors.

Fig. 6 Multiplier errors.
**Fig. 7 Multiplier frequency response.**

**Fig. 8 Noise performance with 750 MHz IF.**
4 Conclusions

Preliminary results indicate that a phase detector with appropriate correction can meet the requirements for the system. The analogue multiplier seems to be easier to correct than the double balanced mixer, and the noise for the multipliers seems to be manageable through a summing scheme. As similar results were obtained at 250 MHz and 750 MHz, and since the components for down conversion from 30 GHz are more easily realizable at 750 MHz, the latter frequency has been chosen.

Work on characterizing phase detectors will continue. It is hoped to further reduce the noise contributions of both the phase and amplitude detectors. A narrow-band IF phase measurement system with better amplitude invariance is required. Additional devices should also be evaluated. However, as these first results have allowed us to choose an IF, it is now possible to design the RF part of the system in more detail. This is now underway.

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References


