PRECISION BEAM TIMING MEASUREMENT SYSTEM FOR CLIC SYNCHRONIZATION

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Abstract

Very precise synchronization between main and drive beams is required in CLIC to avoid excessive luminosity loss due to energy variations. One possibility to accomplish this would be to measure and correct the drive beam phase. The timing reference for the correction could be the beam in the transfer line between the injector complex and the main linac. The timing of both main and drive beams will have to be measured to a precision in the region of 10 fs. The aim is to achieve this by means of a beam measurement at 30 GHz with the signal mixed down to an intermediate frequency (IF) for precise phase detection. The RF and IF electronics are being developed and tests will be carried out in CTF3.

INTRODUCTION

The Compact Linear Collider (CLIC) [1] requires a very tight tolerance on the timing jitter between main and drive beams [2]. Errors lead to energy variations in the main linac and a subsequent reduction of luminosity. A jitter of 15 fs will give a luminosity reduction of around 2 %. It is extremely doubtful that the required tolerance could be met without feedback, feedforward or both types of beam-based correction. For example, the drive beam phase could be measured before, and then corrected after, one or more drive beam turn-arounds. Correction could be done using RF structures, either with deflecting cavities or by varying the energy before the final drive beam bunch compressor.

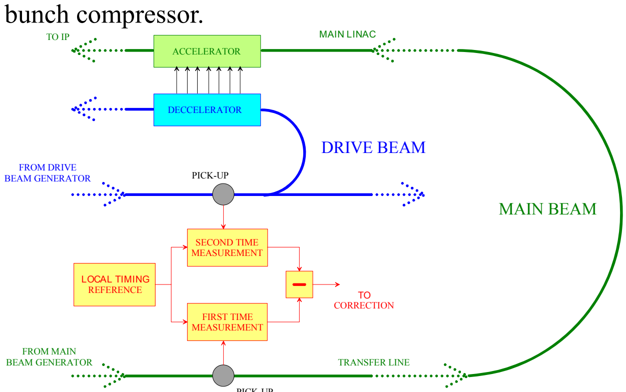

Figure 1: CLIC synchronization using local reference.

Although optical fibre phase distribution systems are approaching the required level of stability [3] (albeit for relatively short links), an alternative scheme for CLIC that appears to be very attractive is to use the beam in the transfer line between the injector complex and the main linac as the timing reference (Fig. 1). This way, errors of the main beam phase with respect to the master RF oscillator would also be taken into account and compensated. In the case where the first section of the drive beam is used to power the main beam bunch compressor this could be used as a phase reference. A precision local clock would be required to keep time from the arrival of the reference until the end of the drive beam train, 92 µs later. Clocks that give an error of well under 10 fs over this time are available. In addition to this requirement, a precision beam timing measurement is vital to the scheme. It would be advantageous to perform this measurement at the main linac's RF frequency (30 GHz) in both linacs. Measurement of the drive beam with a 30 GHz pick-up would anyway be desirable or even essential for monitoring the amplitude of this frequency component as it also needs very tight control.

The goal of the work described in this paper is to demonstrate the feasibility of a high precision beam phase measurement at 30 GHz.

PHASE DETECTION

Requirements and Options

We require a phase measurement precision of 0.1^{o} and a bandwidth in the region of ± 50 MHz. The latter requirement is to permit intra-pulse compensation within the 70 ns drive beam pulses up to the bandwidth of the CLIC accelerating structures. The usable phase range can be quite small as it can be assumed that the system is fairly well synchronized to better than $\pm 5^{o}$. A further aim is to maintain the full precision over a dynamic range of at least 6 dB. Variable attenuators can be used to adjust the beam signals to within this range.

Phase detection is commonly performed digitally either after direct conversion or via an IF (intermediate frequency). Unfortunately, the combination of phase accuracy, bandwidth and dynamic range rule out this option at present. The use of diode mixers or Gilbert cell transistor analogue multipliers [4] is therefore being studied. Careful characterization of these devices is required in order to ascertain their suitability and for this an automated test set-up has been built.

One solution that looks promising is to use an array of analogue multipliers, their outputs being summed to reduce noise. The sum signal is then digitized after which a correction can be made for any non-ideal amplitude dependence.

Characterization

The test set-up that has been built (Fig. 2) is designed to characterize phase detectors for frequency response, amplitude dependence and noise. It operates between 200 MHz and 1 GHz with bandwidths up to 100 MHz.

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 narrowband phase measurement of the IQ modulator outputs in order to relate phase measurements at different amplitude levels to each other. Having thus established the narrowband 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 set-up can only measure narrowband phase with about a 0.1° resolution. The data are thus only preliminary as a more precise narrowband phase measurement will be required to obtain an accurate amplitude correction.

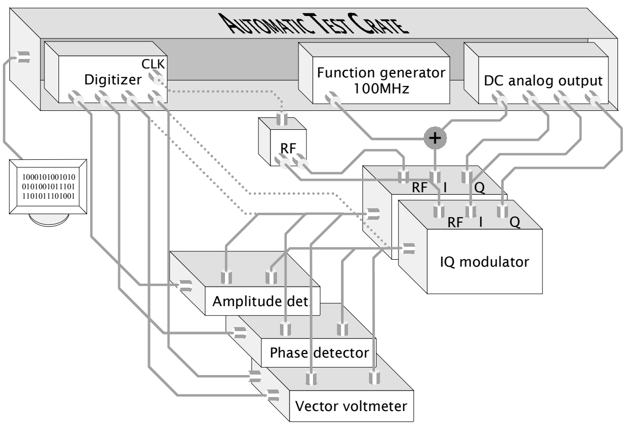

Figure 2: Automatic test set-up.

The outputs of the phase detector V_ϕ 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_ϕ

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

Results obtained with two summed Analog Devices AD835 analogue multipliers and an Analog Devices AD8318 amplitude detector at 750 MHz are shown in Fig. 3. The plot shows the residual errors between input phase and phase computed from the outputs of the phase detector and the amplitude detector. 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. Frequency response measurements over a 7 dB amplitude range indicate that the multiplier is well behaved to above 50 MHz and to 100 MHz with some correction.

Noise measurements (Fig. 4) 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 √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.

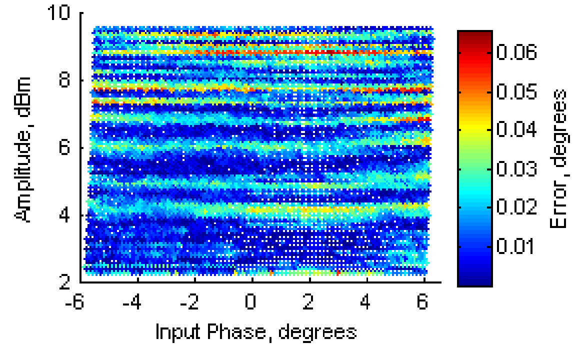

Figure 3: Residual errors with two analogue multipliers.

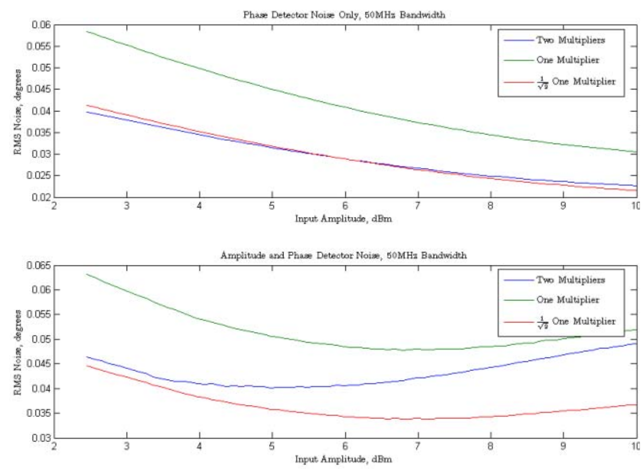

Figure 4: Noise performance with 750 MHz IF.

Improvements

The above results have demonstrated that a phase detector with appropriate correction can meet the requirements for the system and that a relatively high IF of 750 MHz can be used. However a better narrowband phase measurement and improved noise performance are required.

Two 2 GS/s 10-bit cPCI data acquisition cards have been purchased for the beam tests described in the following section and tests have been carried out to see if they can also be used for the narrowband calibration. Instead of using a vector voltmeter, the two outputs of the IQ modulators would be sampled directly at 750 MHz (dashed lines in Fig. 2). Results suggest that they will be just sufficient. The r.m.s. phase variation between two channels digitizing the same 750 MHz carrier was 0.006° in a 300 Hz bandwidth over a 7 dB amplitude range. During one hour of constant amplitude running a phase drift of 0.008° was typically observed. This is about the time required to obtain all the data for one circuit.

The improved narrowband characterization will be used to test a newly developed detector PCB which is designed for lower noise. It contains arrays of eight phase detectors and eight amplitude detectors.

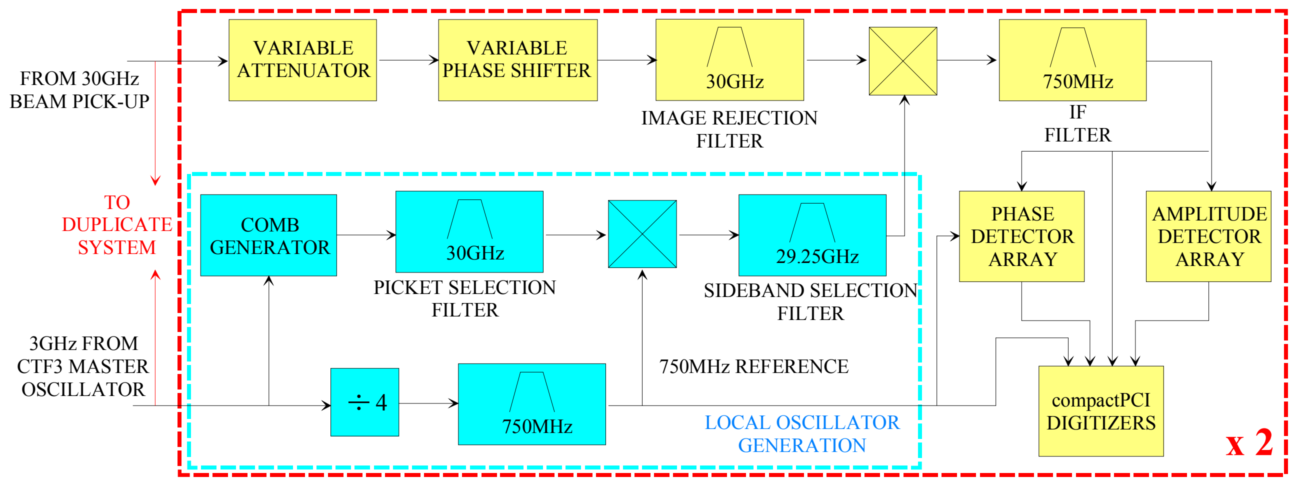

Figure 5: System for tests with beam in CTF3.

COMPLETE SYSTEM

In addition to continuing phase detector work, the complete system necessary for tests with beam in CTF3 [5] is now being built. A simplified block diagram is shown in Fig. 5. Since the jitter of the CTF3 beam will exceed the anticipated precision, two systems will be made to measure the same beam signal and their outputs will be compared. However they are not completely independent as they share the same 3 GHz master oscillator. The comparison will thus remove the jitter of this source that remains coherent. This choice was made for reasons of economy. As microwave sources with an acceptably low jitter are available commercially at this frequency, the use of independent oscillators is not a feasibility issue. On the other hand, the frequency multiplication up to 30 GHz is duplicated and two different diodes are currently being evaluated for this task.

Variable attenuators and phase shifters will be used to adjust the detectors to within their operating range and will also permit observation of the effects of different amplitude and phase offsets between the two systems. With the exception of the digitizers, the electronics will be installed in a rack stabilized in temperature to ± 0.1°C. The input, picket selection and local oscillator sideband selection filters will all be constructed from invar and have group delay variations of less than 10 fs/°C. As the IF filtering requirements are very relaxed, stability should not be a concern.

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 [6] structure can be used. It is already installed for 30 GHz power production and has more than sufficient bandwidth.

CONCLUSIONS

CLIC synchronization will require precision beam timing measurements of both main and drive beams. We hope to demonstrate that the necessary accuracy can be obtained by measuring beam phase from pick-ups operating at the main linac's RF frequency. Up to now the work has concentrated on finding a suitable method of IF phase detection. An analogue technique followed by a digital correction appears the most suitable. The complete system is now being built for tests with beam in CTF3.

ACKNOWLEDGEMENTS

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