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Constant Fraction Discriminator for NA62 experiment at CERN

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Abstract: A new Constant Fraction Discriminator with additional Time over Threshold measurement capabilities will be presented. It operates in a wide dynamic range of 1:150, with an excellent time resolution of better than 70 ps over one order of magnitude of the input signals. It is highly customizable for different signal shapes and thresholds, using remotely-programmable parameters for Detector Control System commands. Two outputs, each in the Nuclear Instrumentation Module and Low Voltage Differential Signaling standards, provide a precise signal arrival time and Time over Threshold information with programmable thresholds. The technical specification and performance measured with cosmic rays and in the high-intensity NA62 experiment will be reported.

Keywords: Front-end electronics for detector readout; Analogue electronic circuits

2024 JINST 19 C03002

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Contents

1 Introduction

A key functionality of the Constant Fraction Discriminator (CFD) is to precisely determine the timing of signals in particle detectors and other measurement systems. The leading-edge-discriminator timing performance suffers from time walk, caused by a varying signal amplitude while the threshold is fixed. The original CFD was proposed to eliminate this time walk by introducing a variable threshold following the signal amplitude. A constant fraction of the input signal is subtracted from the full-amplitude delayed input signal. The final signal has a zero crossing point (walk) which is fixed for signals with different amplitudes.

The schematic sketch of the CFD functionality is shown in figure 1. The two important parameters are signal delay T_d and signal fraction k, which depend on the rise time of the signal and its shape.

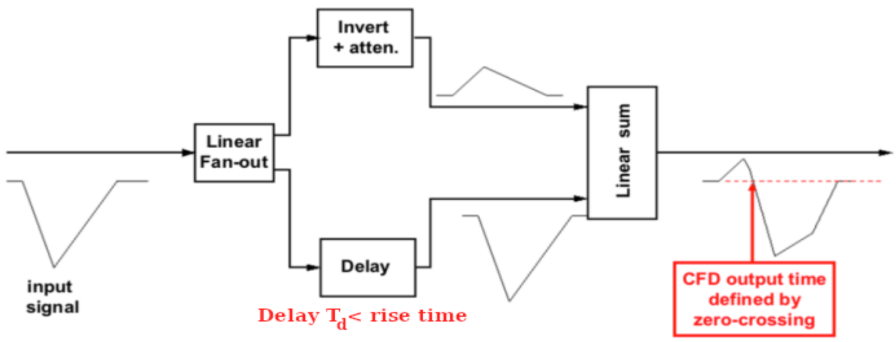

Figure 1. Illustration of the CFD functionality.

2 Motivation and requirements

The NA62 experiment at the CERN SPS accelerator is the world's flagship experiment in kaon physics, measuring $K^+ \to \pi\nu\bar{\nu}$ — one of the "golden modes" in flavour physics [1]. One of the limitations of the experiment is a background from kaon decays happening upstream of the fiducial volume [2]. This "upstream background" primarily comes from $K_{2\pi}$ ($K^+ \to \pi^+\pi^0$) and $K_{3\pi}$ ($K^+ \to \pi^+\pi^+\pi^-$) decays where some of the decay products are absorbed in the collimator, while a charged pion can propagate to the decay volume. A detector made of scintillating tiles (VetoCounter) with precise timing was proposed to detect the "lost" particles from these upstream decays. The VetoCounter has to detect the charged pions and photons from π^0 decays, while mitigating the random veto from the muon halo. It consists of three stations: the first and second are separated by a lead barrier to convert photons into e^+/e^- which can be detected in the scintillator, while the third station is located behind the 1 m thick iron collimator which absorbs all particles except muons. In total, the VetoCounter consists of 33 scintillating tiles, each read-out by two fast photomultipliers (PMTs) Hamamatsu R9880U-110 with a rise time of ~ 1 ns. Due to the high rate environment, precise timing at the level of 200 ps is required. As the VetoCounter should detect both the minimum ionizing particles (MIP) and electron showers from photons converted in the lead, a wide dynamic range of input signal (1:30) is required. To distinguish between the various particles crossing the detector, two independent thresholds with the Time-over-Threshold (ToT) measurement should be provided. These requirements led to the development of the new high-performance CFD.

3 The active CFD for NA62 experiment

3.1 Design description

To preserve the high dynamic range of the input signals, an active CFD is used. The input signal is not attenuated but the delayed signal is amplified by an inverse attenuation ratio. Two antiparallel fast-switching diodes limit signal amplitudes for the internal stages. This guarantees that the chip stays within its specified maximum voltage range while allowing for a wide input voltage range. Input signal is amplified by a programmable amount using an inverting variable gain amplifier. The amplifying range is 1:10 which corresponds to inverted factor between 1 and 0.1. On the second path, the input signal is delayed in a built-in microstrip delay line with a delay of ~ 0.2 ns, or by soldering an external miniature coaxial cable. The delayed and amplified signals are summed in a fully-differential summing amplifier and are then presented to the CFD decision comparator. A Window comparator opens a gate for the CFD comparator only for signals with amplitudes exceeding window threshold, thus reducing random triggering. A spourious-free dynamic range amplifier connected to an input signal provides clean pulses for signal width measurement, for two output thresholds — Low and High. All decision logic is in Emitter-coupled logic standard to guarantee sufficient speed. Two output standards (Nuclear Instrumentation Module — NIM and Low Voltage Differential Signaling — LVDS), each with CFD and ToT information, are provided for the Low/High thresholds. A block diagram of the circuit is shown in figure 2.

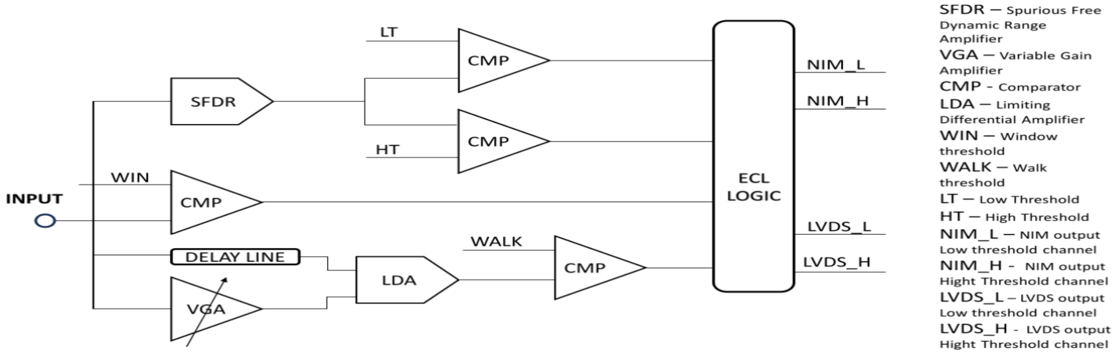

Figure 2. A block diagram of the CFD circuit.

3.2 CFD board

The CFD is an independent PCB with an SMA input connector, five potentiometers to set various parameters (see section 3.3), two coaxial output connectors, a power connector and an edge connector (see figure 3). The coaxial connectors provide NIM signal outputs of the comparator when the input passes the Low/High threshold. The edge connector is plugged into the Motherboard through which it receives the power and Detector Control System (DCS) commands and sends out the LVDS signals for the thresholds Low/High.

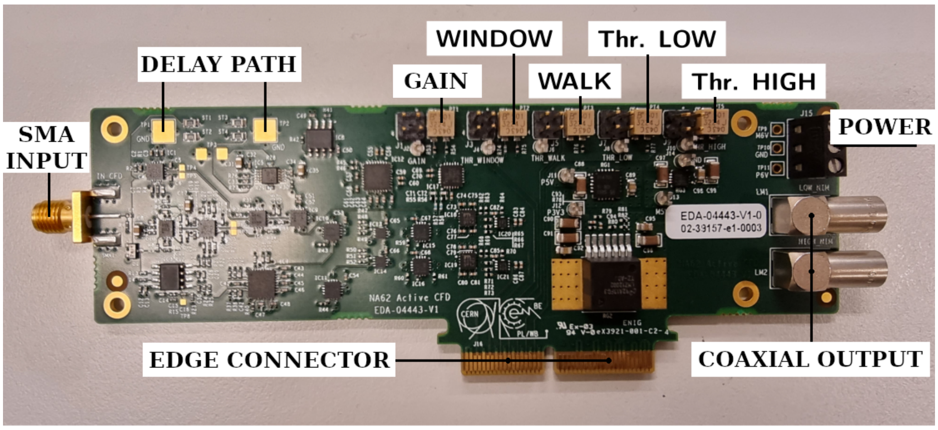

Figure 3. The active CFD with the annotated components.

The Motherboard is a standard EURO 6U card, hosting 16 CFD boards. It provides the power to the CFD boards and communication with the DCS based on ATmega microcontroller with 100 Mb Ethernet. The LVDS signals of Low/High thresholds from the CFD boards are collected and grouped into the 32-channel SCSI III connector. The Motherboard is equipped with four fans to provide cooling for the CFD boards.

3.3 Operation

The presented active CFD has several controllable parameters, which can be set manually by the potentiometers on the board or remotely via DCS commands. The local/remote set of parameters is inhibited by the jumpers on the board. For the remote mode, a check of the parameter values is returned as a response to the set command.

2024 JINST 19 C03002

The Window parameter sets a threshold that triggers the functionality of the CFD only for the duration of the valid input signal, which helps to prevent oscillations (see section 3.1). A Gain parameter, previously refereed to as k, characterizes the amplification of the inverted signal, which is important to tune for different input pulse shapes. The Walk parameter represents the threshold around the zero-crossing after the sum of two signal lines. The Low/High thresholds determine the output pulse width. The rising edge of the output signal is always defined by the CFD time, while the trailing edge is dependent on the input signal amplitude. If the Low/High threshold is not passed, while the input pulse has crossed the Window threshold and hence activated the CFD, the width of the output pulse is fixed, otherwise it corresponds to the ToT measurement. One can also vary T_d by choosing internal PCB traces of different lengths on the prepared pads on the board.

4 Performance

To measure the performance of the CFD, a test with an Arbitrary Waveform Generator (AWG) Tektronix AWG5012C was done. A pulse resembling the PMT signal was simulated in the AWG, which outputs two identical signals and a marker. One generated signal went to the CFD, one went to the scope MSO-64 (2.5 GHz, 25 GS/s) and the marker was used for triggering. Then, varying the pulse height by more than an order of magnitude, a difference between the generated pulse and the output from the CFD at 50% of the amplitude was measured. Figure 4 shows the generated signal and outputs from the CFD, together with the distribution of the time difference for a given pulse amplitude with a variation of just a few ps. The systematic error due to double AWG output was about 10 ps. Figure 5 shows the time delay between input and output pulses as a function of the pulse amplitude. Within the amplitude range from 70 mV to 1000 mV the CFD resolution is better than 70 ps. With higher amplitude the time delay grows linearly because the input protection diode is activated and the amplifier with output signal amplitude limit is saturated, hence biasing the signal. For lower amplitudes the increased noise/signal ratio deteriorates the performance of the CFD.

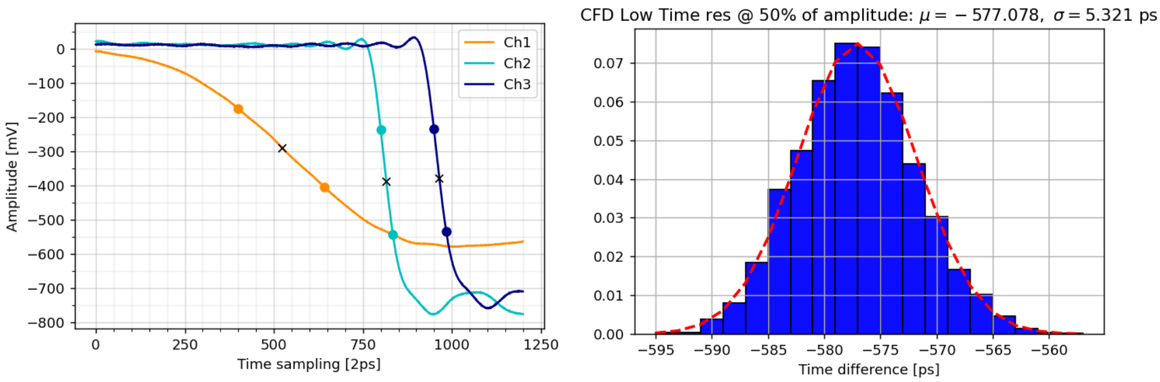

Figure 4. Left: the example of the investigated pulses, with orange line representing the input signal and cyan/blue lines corresponding to NIM outputs of thresholds LOW/HIGH. The dots show 30%/70% of the pulse, while the cross is in the 50% of the pulse amplitude. Right: time resolution of the CFD for a fixed input signal.

The time resolution as functions of Gain and Walk was also measured. The lab setup consisted of 4 scintillating tiles one on top of each other, each read out by two PMTs detecting cosmic rays. Signals in top and bottom tiles in coincidence defined the trigger. Signals from the PMTs of the middle tiles

2024 JINST 19 C03002

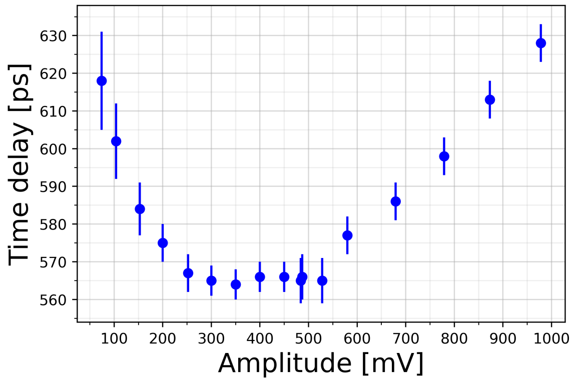

Figure 5. Time delay between generated signal and CFD output signal as a function of the pulse amplitude. The difference of the time delay corresponds to the CFD time resolution.

were fed through the CFD into the oscilloscope. The time of the internal tile was defined as an average of the times of two PMTs attached to that tile. Measurement of the time difference between rising edges defined by the CFD between internal tiles as a function of CFD parameters is shown in figure 6. As one would expect, the best time resolution is at the low Walk threshold. The best performance of the Gain parameter depends on the shape of the input pulse.

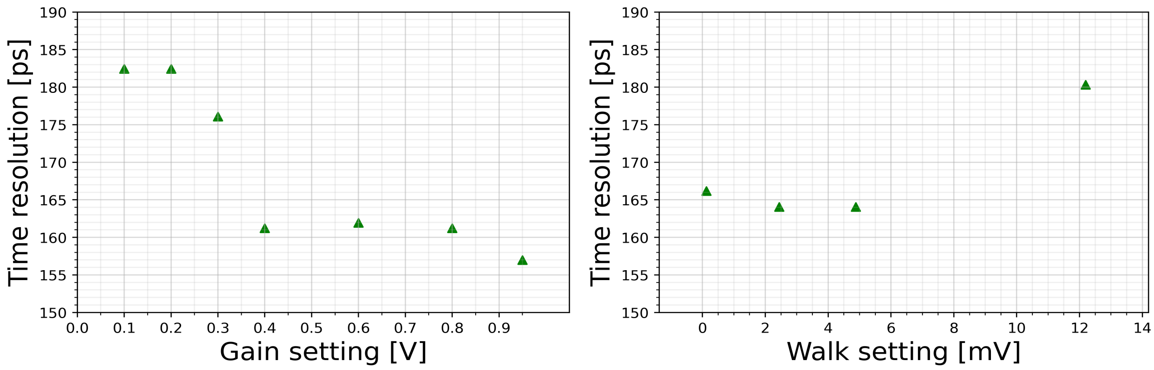

Figure 6. Time resolution of CFD as a function of its parameters — Gain (left) and Walk (right). The time resolution is dominated by the input signals from the PMTs and scintillators.

5 CFD in NA62 experiment

The CFDs for the VetoCounter detector in the NA62 experiment were installed in May 2022. The NIM output signals are send to the standard NA62 read-out based on TEL62 [3] TDC boards. The LVDS output signals are processed by newly-developed FPGA-based TDCs connected via optical links to a trigger-less future read-out based on FELIX [4] (co-developed with ATLAS). Thanks to the double read-out, the new TDCs were fully commissioned.

Besides understanding the composition of the upstream background at the NA62 experiment, ToT measurements provided by the CFD can be utilized for the calibrating the detector. During a special muon run, the high voltage supplying the PMTs was varied and the fraction of events passing Low/High thresholds, set to -60 mV/-80 mV, was measured. The resulting HV scan is shown in figure 7. From the scan, one can set the HV of the PMTs to correspond to a specific amplitude for the MIP.

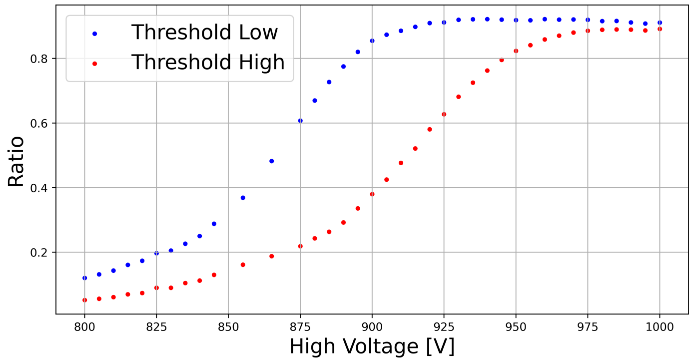

Figure 7. Fraction of MIPs passing the threshold LOW/HIGH as a function of PMT HV.

6 Conclusion

The presented CFD developed for the NA62 experiment at CERN has a time variation of few tens of ps over a wide range of amplitudes. The CFDs were installed in May 2022 and successfully commissioned in the experiment. All requirements were met and no major issues were observed during the detector operation. The optimal parameter values were found and set on the CFDs using the cosmic rays measurement. The calibration of the VetoCounter was performed thanks to the ToT measurement during the muon run.

The CFD demonstrated its functionality and performance in the NA62 experiment and can be used in other installations, where the precise timing over a wide range of the input amplitudes is required.

References

[1] NA62 collaboration, *The beam and detector of the NA62 experiment at CERN*, 2017 *JINST* **12** P05025 [arXiv:1703.08501].

[2] NA62 collaboration, *Measurement of the very rare* $K^+ \to \pi^+ \nu\bar{\nu}$ *decay*, *JHEP* **06** (2021) 093 [arXiv:2103.15389].

[3] F. Spinella et al., *The TEL62: A real-time board for the NA62 Trigger and Data AcQuisition. Data flow and firmware design*, in the proceedings of the *19th IEEE-NPSS Real Time Conference*, Nara, Japan (2014), p. 1–2 [DOI:10.1109/RTC.2014.7097525].

[4] J. Anderson et al., *A new approach to front-end electronics interfacing in the ATLAS experiment*, 2016 *JINST* **11** C01055.