SAMPIC: a readout chip for fast timing detectors in particle physics and medical imaging

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Abstract. We describe the new fast timing readout chip SAMPIC developed in CEA Saclay and in LAL Orsay (France) as well as the results of differents tests performed using that chip.

1. Introduction: Timing measurements in particle physics and in medical imaging
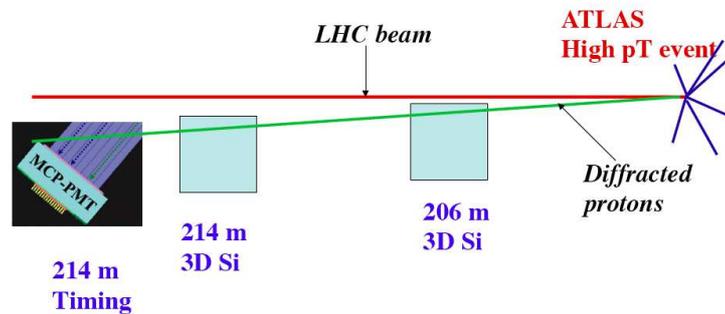
Figure 1. Scheme of the AFP proton detector in ATLAS. The same detector is implemented on the other side of ATLAS. A similar detector is installed in CMS/TOTEM.

At the Large Hadron Collider (LHC) at CERN, the most energetic proton-proton collider in the world with a center-of-mass energy of 14 TeV, there are special classes of events where protons are found to be intact after collisions. These events are called "diffractive" in the case of gluon exchanges. They can originate from photon exchanges as well. The physics motivation is a better understanding of diffraction in terms of QCD [1] and the search for beyond standard model physics such as the existence of extra-dimensions in the universe via anomalous couplings between photons, W and Z bosons [2]. The intact protons scattered at small angles can be measured in dedicated detectors, hosted in roman pots, located close to the beam and far away from the main central ATLAS or CMS detectors. In order to measure rare events at the LHC, the luminosity (or in other words the number of interactions per second) has to be as large as possible. In order to achieve this goal, the number of interactions per bunch crossing can be very large, up to 40-70 during the LHC running of 2015-2017 as an example. The projects to measure intact protons at high luminosity in the ATLAS and CMS/TOTEM experiments

are respectively called AFP (ATLAS Forward Physics) and CT-PPS (CMS/TOTEM-Precision Proton Spectrometer) [3]. Timing measurements are crucial at the LHC in order to determine if the intact protons originate from the main hard interaction or from secondary ones (pile up). Measuring the proton time-of-flight with a typical precision of 10 ps allows constraining the protons to originate from the main interaction point of the event (hard interaction) with a precision of about 2.1 mm. For a pile up of 40 (which means about 40 interactions occuring in the same bunch crossing at the LHC), such a precision on time-of-flight measurements leads to a reduction in background of a factor of about 40 [4].

Timing measurements have also many applications in drone technology and in medical imaging as an example. The "holy grail" of medical imaging would be a PET detector with a 10 ps timing precision. With such an apparatus, image reconstruction is no longer necessary (the analysis can be performed online) since many fake coincidences can be suppressed, only attenuation corrections are needed, and real time image formation can be performed.

In order to achieve a 10 ps precision, many steps are needed going from the detector to the electronics and the readout software. In this article, we will concentrate on the achievement concerning the picosecond timing electronics that is currently being done in IRFU/SEDI Saclay and in LAL-Orsay [5, 6].

2. SAMPIC: SAMpler for PICosecond time pick-off
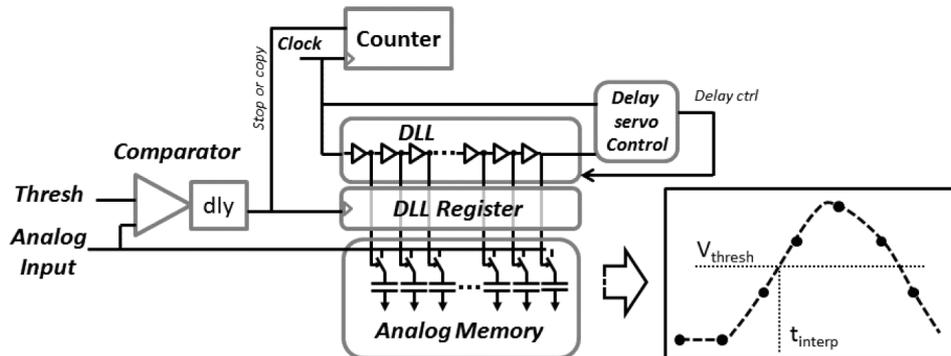
Figure 2. Scheme of the SAMPIC chip.

Before SAMPIC, the most performant Time to Digit Converters (TDCs) used digital counters and Delay Line Loops (DLLs). The timing resolution is limited by the DLL step and with most advanced Application Specific Integrated Circuit (ASICs), one gets a resolution of about 20 ps (new developments at CERN target 5 ps). The inconvenient is that a TDC needs a digital input signal: the analog input signal has to be transformed into a digital one with a discriminator which means that the timing resolution will be given by the quadratic sum of the discriminator and the TDC timing resolutions, thus leading to worse timing resolutions.

A new approach had to be developed using the principle of a wafeform based TDC. The idea is to acquire the full waveform shape of a detector signal in an ASIC dedicated to picosecond timing measurements. The input signal range has to be between 0.1 and 1. V with a fast rising time up to 1.ns in order to get the best possible performance of SAMPIC. The present version of the chip holds 16 channels (50 Ω terminated) with independent dead time. The possible trigger modes are either self triggered or triggered externally. Each channel includes an analog memory (64 cells) and recording is triggered by a discriminator. A Gray counter associated to DLLs allows assigning a time to the different samples and an ADC provides the conversion into a digital signal.

Figure 3. Picture of the SAMPIC chip and its acquisition board.

Three timing measurements with different precision are performed in SAMPIC. The time stamp Gray counter has a 6 ns step (it samples the reference clock), the DLL 150 ps (it defines a region of interest) and the waveform shape a few ps RMS after interpolation between the acquired points (they are acquired on a 64 step analog memory).

As we already mentioned, SAMPIC acquires the full waveform shape of a detector signal. The discriminator is used only for triggering, not for timing, and thus there is no jitter originating from the discriminator. All the information concerning the signal is kept in SAMPIC, and it is possible to use offline signal processing algorithms in order to improve the timing resolution. It can also be used to obtain other signal characteristics such as the deposited charge. In the present version, SAMPIC suffers an important dead time per channel due to the ADC conversion of about 1 μs. It will be reduced by about one order a magnitude in the next version of SAMPIC, using in particular the so called "ping-pong" method and analog buffering. Two SAMPIC chips can be hosted in a mezzanine board developed in LAL, Orsay, leading to a 32-channel system. The input into SAMPIC is sent via MCX connectors. SAMPIC can be read out using an USB-Ethernet-Optic fiber readout is also provided. A 5 V voltage power supply is the only element needed to run the mezzanine board and the readout software runs on Windows or Linux. A scheme of SAMPIC is given in Fig. 2 and a picture of SAMPIC together with its acquisition board in Fig. 3.

SAMPIC is quite cheap (about 10 Euros per channel) with respect to a few 1000s Euros for previous technology, which means that it can be used in large scale detectors such as PET for medical applications.

As a reference, a table giving the parameters of the SAMPIC chip is given in Fig. 4.

3. SAMPIC performance
3.1. Electronics tests
In this section, we describe the SAMPIC performance obtained from pure electronics tests. The maximum signal size is about 1.V, and after corrections, the average noise is quite low, of about 1 mV RMS (the noisiest cells being 1.5 mV RMS), which means a dynamic 10 bits RMS.

The SAMPIC cross talk was measured by sending a signal of 800 mV with a 300 ps rise time on one channel and reading out the neighbouring channels. The cross talk was found to be

		Unit
Technology	AMS CMOS 0.18μm	
Number of channels	16	
Power consumption	180 (1.8V supply)	mW
Discriminator noise	2	mV rms
SCA depth	64	Cells
Sampling Speed	<3-8.4 (10.2 for 8 channels only)	GSPS
Bandwidth	1.6	GHz
Range (Unipolar)	1	V
ADC resolution	8 to 11 (trade-off time/resolution)	bit
SCA noise	<1.3	mV rms
Dynamic range	9.6	Bit rms
Conversion time	0.2-1.6 (8bit-11bit)	μs
Readout time (can be probably be /2)	25 + 6.2/sample	ns
Time precision before correction	15	ps rms
Time precision after timing INL correction	< 5	ps rms

Figure 4. Parameters of the SAMPIC chip.

less than 1%. The quality of sampling was tested using a sinus wave signal, and the signal was perfectly reproduced without corrections at a sampling frequency of 10 Gigasamples per second. The sampling speed in SAMPIC is possible between 3 and 8.2 Gigasamples per second on 16 channels (up to 10 Gigasamples per second for 8 channels).

The timing resolution was studied by using two different channels of SAMPIC. The same signal was sent on both channels, one being delayed compared to the other one using a delay box or longer cables. The pulse had an amplitude of about 1.2 V, and we used the 6.4 Gigasamples per second configuration. The RMS of the time difference between the two signals as a function of delay is given in Fig. 5 using two different offline algorithms to reconstruct the time difference (CDF as constant fraction discriminator and CC as cross correlation using a linear or a spline interpolation between the different points measured by SAMPIC). The time resolution is quite flat as a function of the delay between the two signals and is about 5 ps, leading to a time resolution per channel of about 4 ps.

A similar study of the timing resolution versus the signal amplitude is shown in Fig. 6. The signal has to be above 450 mV in order to obtain the best timing resolution possible of about 4 ps.

3.2. Timing resolution using detectors
The second series of tests was performed by plugging SAMPIC into a real detector. We used a laser signal splitted in two, and going through two fast Si detectors [7]. The time difference between the two channels was measured using SAMPIC. The result is shown in Fig. 7 using the offline cross correlation algorithm. The time resolution is about 30 ps. It is of course dominated by the fast Si detectors, the resolution of SAMPIC being of the order of 4 ps. Additional studies are being performed in beam tests using diamond detectors leading to a time resolution of 80 to 90 ps [8].
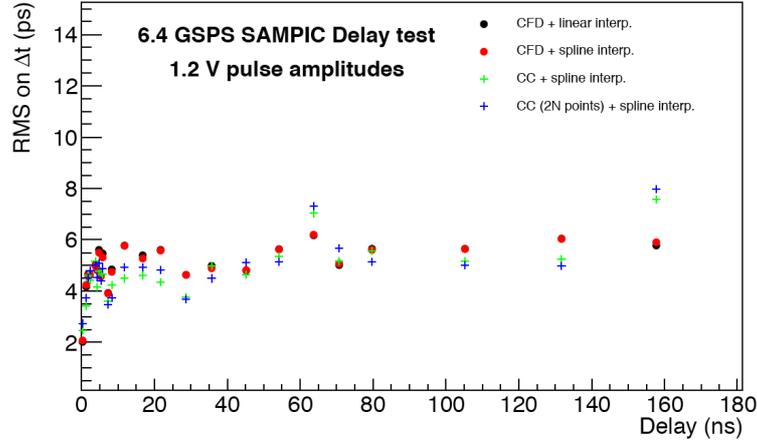
Figure 5. RMS on the time difference between two signals, one being delayed with respect to the other using two offline algorithms (Constant Fraction Discriminator (CFD) and cross correlation (CC)) using a linear or a spline interpolation.
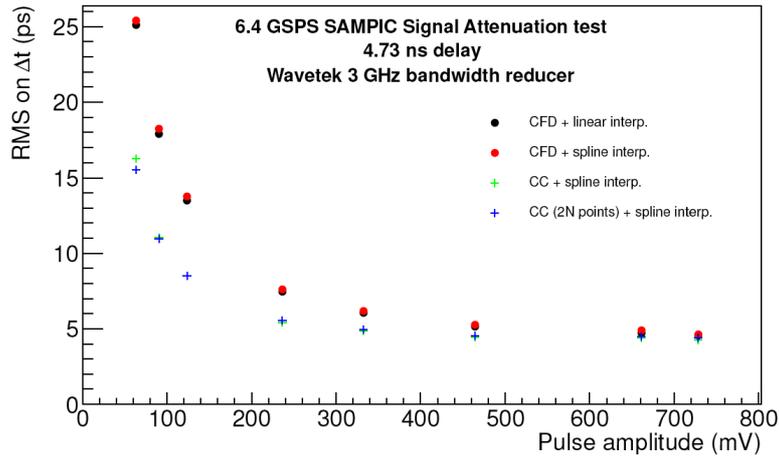
Figure 6. RMS on the time difference between two signals as a function of the signal amplitude using two offline algorithms (Constant Fraction Discriminator (CFD) and cross correlation (CC)) using a linear or a spline interpolation.

4. Conclusion

A self triggered timing chip demonstrator has been designed and characterised with 1.6 GHz bandwidth, up to 10 Gigasamples per second, low noise and of the order of 4 ps timing resolution. The chip is now ready and can be used for tests. Tests already started within the AFP, CT-PPS and CMS/TOTEM projects using quartz, diamond and Si detectors. Work is still going on in order to improve the chip concerning the DAQ system optimisation (firmware and software) and the improvement of the dead time using the "ping-pong" method. SAMPIC can now be used in many applications for tests in addition to particle physics for instance in medical imaging, drones, in detectors including many channels due to the low cost per channel.

Fast Si detectors (g=10) + Charge Sensitive Amplifier
SAMPIC 6.4 GSPS, channels self-triggered
Offline cross-correlation algorithm

Entries	9986
Mean	426.1
RMS	41.62
Constant	768 ± 9.5
Mean	426 ± 0.4
Sigma	41.34 ± 0.30
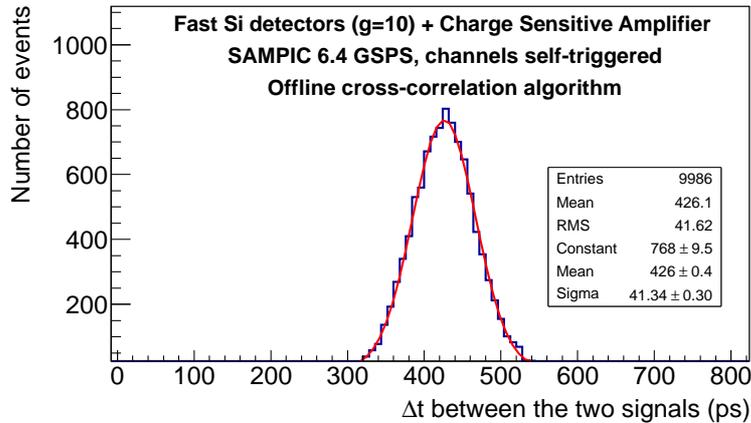
Figure 7. Time difference between two SAMPIC channels reading out Si detectors, a laser signal splitted in two going through the two Si detectors.

Acknowledgments

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