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Results with the TOFHIR2X revision of the front-end ASIC of the CMS MTD Barrel Timing Layer

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The CMS Detector will be upgraded for the High-Luminosity LHC to include a MIP Timing Detector (MTD). The MTD will consist of barrel and endcap timing layers, BTL and ETL, respectively, providing precision timing of charged particles. The BTL sensors are based on LYSO Ce scintillating crystals coupled to SiPMs that are read out by TOFHIR2 ASICs in the front-end system. A resolution of 30 ps for MIP signals is expected at the beginning of HL-LHC operation degrading to 60 ps at the end of operation due to the SiPMs radiation damage. Relative to the first version of the front-end ASIC, TOFHIR2X implements improved circuitry for mitigation of the SiPM dark current noise as well as a new current mode discriminator. We present an overview of the TOFHIR2 requirements and design, simulation results and the first measurements with TOFHIR2X silicon samples coupled to LYSO/SiPM prototype sensors.

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Abstract– **The CMS Detector will be upgraded for the High-Luminosity LHC to include a MIP Timing Detector (MTD). The MTD will consist of barrel and endcap timing layers, BTL and ETL, respectively, providing precision timing of charged particles. The BTL sensors are based on LYSO:Ce scintillating crystals coupled to SiPMs that are read out by TOFHIR2 ASICs in the front-end system. A resolution of 30 ps for MIP signals is expected at the beginning of HL-LHC operation degrading to 60 ps at the end of operation due to the SiPMs radiation damage. Relative to the first version of the front-end ASIC, TOFHIR2X implements improved circuitry for mitigation of the SiPM dark current noise as well as a new current mode discriminator. We present an overview of the TOFHIR2 requirements and design, simulation results and the first measurements with TOFHIR2X silicon samples coupled to LYSO/SiPM prototype sensors.**

I. INTRODUCTION

The Phase II Upgrade program of the CMS experiment at the CERN Large Hadron Collider includes the construction of a new Minimum Ionizing Particles (MIP) Timing Detector (MTD) to measure the time of charged particles with high precision [1]. This MTD will provide timing of charged particles with high precision allowing to extend to the time domain the association of charged particles to the ~200 concurrent proton collision vertices occurring at each bunch crossing in the High-Luminosity LHC (HL-LHC).

To accomplish this objective a timing layer will be added in front of the CMS calorimeters [2]. In the barrel section, the Barrel Timing Layer (BTL) is a thin standalone detector based on LYSO:Ce crystals read out with silicon photomultipliers (SiPMs). With an internal radius of 114.8 cm and an outer radius of 118.8 cm, the BTL has a length of 496 cm covering the pseudorapidity region up to $|\eta|=1.48$ with a total active surface of about 38 m^2. The individual cell consists of a LYSO crystal bar with $3\times3\times57$ mm^3 with two 3×3 mm^2 SiPMs glued at each end. The full BTL detector has about 330 thousand SiPM channels.

LYSO is a scintillating crystal with high density (>7.1 g/cm^3), large light yield (~40k photons/MeV) and scintillation decay time of 40 ns. MIP deposit in the crystal on average an energy of 4.2 MeV. The individual SiPM photo-sensor has 40,000 micro-cells of 15×15 μm^2 each. The Photon Detection Efficiency (PDE) at 420 nm is 20-40% and the gain is 1.5-3.8×10^5 depending on the bias voltage applied. The SiPMs are operated with an over-voltage in the range 1.5-3.5 V optimizing PDE and gain versus Dark Count Rate (DCR). The main drawback of the SiPMs is the increased DCR due to radiation damage. Additional effects include reductions of the gain and PDE after irradiation. To reduce this DCR noise the SiPM are operated at a temperature of -40 ºC and will be periodically annealed at room temperature or higher.

Dedicated ASIC electronics will be used to read out the SiPM arrays. The readout solution uses the new TOFHIR2 chip. The main requirements for the BTL electronics are: (1) to measure MIP timing with a precision of the order of 30 (60) ps at the beginning (end) of HL-LHC operation; (2) to mitigate the effect of large DCR implementing noise cancellation circuitry; and (3) to provide a measurement of the signal amplitude with <5% precision for time-walk corrections. Additionally, the chip has to cope with a MIP input rate of 2.5 M hit/s per channel corresponding to the expected maximum channel occupancy of 7% and to have an output bandwidth of 640 Mb/s. Last but not least, the chip should have a static power consumption lower than 15 mW per channel. A summary of the TOFHIR specification parameters is given in Table I.

A first version of the chip (TOFHIR1) was implemented in technology CMOS 110 nm of the UMC foundry [3]. TOFHIR1 was largely based on the existing TOFPET2 chip [4], allowing the development of detector modules and the validation of system integration within a tight schedule.

TOFHIR2 is a completely new chip developed in technology CMOS 130 nm of the TSMC foundry [5]. This technology has improved behavior under radiation (small shifts in the threshold voltage of transistors and leakage current). The first full version (TOFHIR2A) was developed and tested in 2020 [3]. The performance of TOFHIR2A matches well the simulation expectations. The service blocks, digital readout, front-end

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amplifiers, DCR noise cancellation, TDCs and QDCs are validated, and successful TID and SEU radiation tests are performed [5].

TABLE I. TOFHIR SPECIFICATION PARAMETERS.

	TOFHIR1	TOFHIR2
Number of channels	16	32
Technology	CMOS 110nm	CMOS 130 nm
Voltage supply	1.2 V, 2.5 V	1.2 V
Reference voltages	External	Internal
Radiation tolerance	No	Yes
DCR noise filter	No	Yes
Number of analog buffers	4	8
TDC bin (ps)	20	10
10-bit SAR ADC (MHz)	10	40
I/O links	LVDS	CLPS
L1, L0 Trigger	Yes, No	Yes, Yes
Max MIP rate/ch (MHz)	1	2.5
Max low E rate/ch (MHz)	3	5
Clock frequency (MHz)	160	160

In this paper, we present the results of the measurements of the TOFHIR2X ASIC revision that became available in July 2021. TOFHIR2X has an improved version of the front-end amplifiers and DCR cancelation module, as well as fast current discriminators instead of voltage discriminators, matching directly the current output of the pulse filters, improving the timing performance. In this paper, we concentrate on the measurements that are relevant to assess the modifications introduced in the new version of the ASIC. Otherwise, the overall performance measured with TOFHIR2X remains unchanged relative to what was reported in [5].

II. ARCHITECTURE AND SIMULATION RESULTS

A block diagram of one TOFHIR2 channel is shown in Fig.1. Each ASIC channel contains one pre-amplifier, two post-amplifiers, three leading edge discriminators, two Time-to-Amplitude Converters (TAC), one Charge-to-Amplitude Converter (QAC), one 40MHz 10-bit SAR ADC and local control logic. TACs and QACs are replicated eight-fold to handle Poisson fluctuations of the events rate. The pre-amplifier provides a low impedance input to the sensor's current signal. The input current is replicated into three branches for timing, energy discrimination and charge integration. Pulse filtering is included in the post-amplifiers to mitigate the deterioration of time resolution due to the large DCR induced by radiation and due to pile-up of LYSO pulse tails.

The digital I/O is directly compatible with the CERN's low-power Gigabit Transceiver (lpGBT) [6]. Two output data links each running at 320 Mb/s provide the required bandwidth. Three input links at 80 Mb/s are used for configuration, external triggering and synchronization. The clock frequency is 160 MHz. More details on the ASIC architecture and specifications can be found in [5].

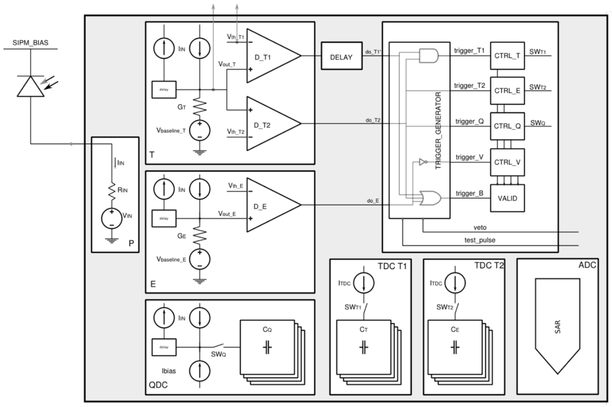

Fig. 1. Block diagram of the TOFHIR2 channel.

The expected time resolution is obtained from a detailed simulation of the ASIC when associated to the sensor (LYSO:Ce scintillating crystals coupled to SiPMs). Several points along the detector lifetime are simulated reproducing the evolution of pulse amplitude and dark count rate due to radiation. At the beginning of life (BoL), the MIP pulses yield 9500 photoelectrons on average, the SiPM gain is 3.8×10^5 and the DCR is negligible. At the end of life (EoL), after the detector has been exposed to a fluence of 2×10^{14} n_{eq}.cm^{-2}, the MIP pulses yield 6000 photoelectrons, the DCR is of the order of 55 GHz and SiPM gain is 1.5×10^5. Fig.2 shows the expected MIP time resolution (for double readout of a LYSO bar) along the detector lifetime obtained with a simulation that includes the effects of photostatistics, SiPM electrical model and jitter, electronics noise, DCR and TDC binning. We conclude that the time resolution is expected to be of the order of 25 ps at the beginning of life degrading to about 65 ps at the end of life.

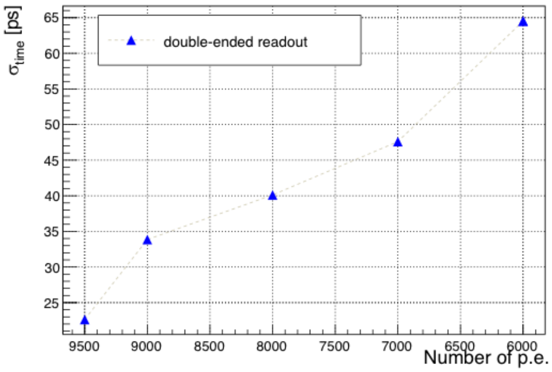

Fig. 2. Time resolution throughout the HL-LHC operation. Due to radiation, the SiPM DCR increases by more than four orders of magnitude at end of life. In order to control this increase, the SiPM over-voltage is reduced gradually, which results in a decrease of PDE and consequently in a decrease of signal yield.

III. EXPERIMENTAL SETUP

The TOFHIR2X ASICs are assembled in the TOFHIR2 test board (Fig.3). Each board includes two TOFHIR2X ASICs, two ALDO2 ASICs (LV and BV regulators) and four SiPM array input connectors. Sensor modules (as shown in Figure 1 on the left) composed of 16 LYSO crystal bars glued at both ends to linear arrays of 16 SiPMs are used in the measurements. The sensor module used in these measurements has a slit on the external wrapping (as shown in Figure 1 on the right) allowing the excitation of the crystal scintillation light with a UV laser (375 nm) emulating the MIP energy deposit. The laser power is adjusted to obtain a given number of photoelectrons per pulse. The calibration of the pulse amplitude is obtained by measuring the SiPM output current. The tests of EoL performance are made with un-irradiated SiPMs, and DCR noise is emulated by using a blue LED. The SiPM HDR2 from HPK, one of the candidates for use in BTL, is used in the present TOFHIR2X characterization tests. The measurements are performed at 20ºC.

Access to data via the ASIC I/O digital links is done using the PETsys Readout System [7]. Flexible cables connect the test board to the FPGA board (FEB/D). The readout system allows to read the two TOFHIR2X ASICs. The FEB/D unit provides the front-end board with all the necessary power, SiPM bias voltages, configuration, and readout. The TOFHIR2X supply voltage and the SiPM bias voltage are regulated by the ALDO2 ASIC [8].

IV. CHARACTERIZATION RESULTS

A. *Power consumption*

The measured consumption of the 32-channel TOFHIR2X ASIC is 330 mA (corresponding to 12.4 mW per channel) when the chip is powered and the clock is active but no signals are present at the chip inputs (static consumption). This value compares reasonably well to the simulated consumption under the same conditions (301 mA). The estimated power consumption from simulation when the chip is subject to the expected high rate of events, namely 2.5 MHz MIP events and 5 MHz low energy events, is 460 mA corresponding to 17.3 mW per channel (static and dynamic consumption).

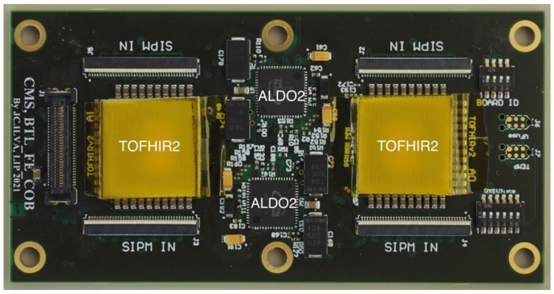

Fig. 3. The BTL front-end board prototype with two TOFHIR2X and two ALDO2 ASICs.

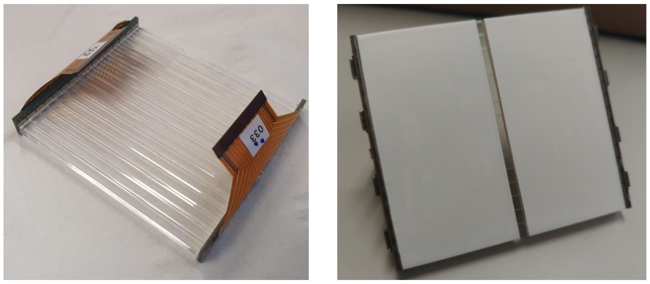

Fig. 4. The BTL sensor module composed of 16 LYSO crystal bars glued at both ends to linear arrays of 16 SiPMs (left). The slit on the external wrapping allows to shine the UV laser on the external wrapping allowing the excitation of the crystal scintillation light with a UV laser (right).

B. *Pulse shape and noise*

We measure the pulse shape when the UV laser yields pulses typical of BoL. The shape of the pulses is obtained by scanning the discriminator T2 threshold (LSB of 1.25 μA). The time of the leading and trailing edges of discriminator output pulse are measured by the TDC1 and TDC2, respectively, allowing to reconstruct the pulse shape. Using this method, the peak of pulse is not observed due to the configurable range of the discriminator threshold. Fig.5 shows good agreement between simulation and data. The slew rate in the rising edge at the level of the optimum threshold for timing measurement is 28.6 μA/ns (to be compared to 28.0 μA/ns in simulation). The observed small discrepancy in the pulse trailing edge is ascribed to a different LYSO decay time in data and in simulation. On the other hand, TOFHIR2X has configurable pulse trimming capability to cope with process mismatch between the NMOS and PMOS branches of the DCR cancellation circuit [5] that allows to fine tune the pulse width on a channel by channel basis.

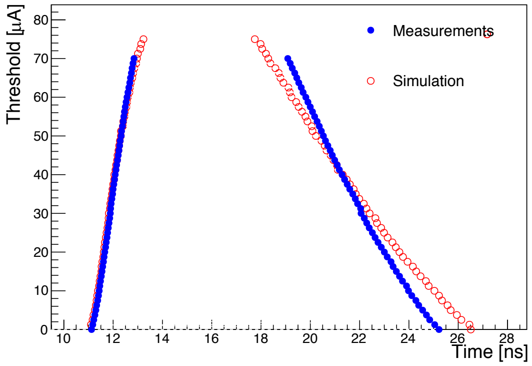

Fig. 5. Pulse shape at the input of the discriminator reconstructed with a threshold scan as obtained with simulation data (red points) and experimental data (blue points).

The combined contributions of the electronics noise and TDC to the time resolution are estimated with laser light shining directly on two naked SiPMs using a beam splitter. The coincidence time resolution (CTR) is measured between the two channels and the channel time resolution is obtained as CTR/$\sqrt{2}$. Fig.6 shows the measured and the simulated channel time resolution as a function of the pulse slew rate (dI/dt). Measurements and simulation are in good agreement. A fit of the data points with the function:

$$\sigma_{\mathrm{t}} = \sigma_{\mathrm{noise}}/(dI/dt) \oplus \sigma_{\mathrm{TDC}}$$

yields σ_{noise} = 0.360 μA and σ_{TDC} = 12 ps. The noise measurement is in nice agreement with the simulation estimation of the electronics noise at the input of the discriminator (0.421 μA). The TDC resolution is in agreement with the direct measurement presented in the next section.

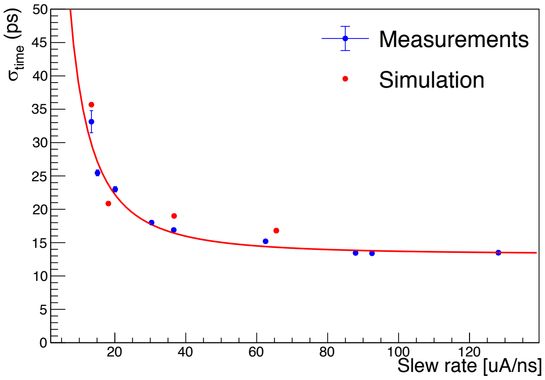

Fig 6. Channel time resolution of laser pulses directly detected by an SiPM as a function of the slew rate of the pulse rising edge in data (red) and simulation (blue).

C. *TDC resolution*

The TDC resolution is derived from coincidences between two TDCs in the chip receiving a common digital test pulse. This method is used to cancel common jitter (e.g. clock jitter). The average TDC resolution estimated in 32 channels of the ASIC is 13 ps, confirming the earlier measurements with TOFHIR2A [5].

D. *Time resolution of MIP equivalent pulses*

In BTL, the timing of a MIP particle is obtained from the average of the two measurements in a single LYSO bar. The bar time resolution may be derived from the CTR of the two channels in the crystal bar (σ_{bar} = CTR/2). The measurement reported here is performed with the UV laser pulse tuned to generate a LYSO pulse with 9500 photoelectrons when the SiPMs are operated at overvoltage of 3.5 V (SiPM gain 3.8×10^5) that is characteristic of the BoL conditions.

Fig.7 shows the bar time resolution as a function of the discriminator threshold for different settings of the delay line in the noise cancellation circuit. At the optimum threshold, we obtain a resolution of 24 ps, in good agreement with the simulation results presented in Fig.2.

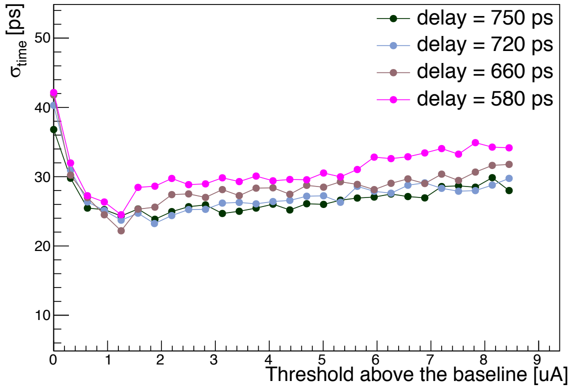

Fig. 7. Time resolution as a function of the discriminator threshold and for different settings of the delay line in the noise cancellation circuit for LYSO pulses with 9500 photoelectrons, typical of BoL conditions.

In order to reproduce the large DCR at EoL, we use background LED blue light emulating the SiPM dark counts. The calibration of the LED light is established by measuring the SiPM current as a function of the LED voltage. The SiPM current is converted in equivalent DCR by taking into account the SiPM gain at the operating over-voltage. We measure the channel time resolution of laser pulses characteristic of EoL conditions using the method described previously, while illuminating the SiPMs with blue light emitted by the LED.

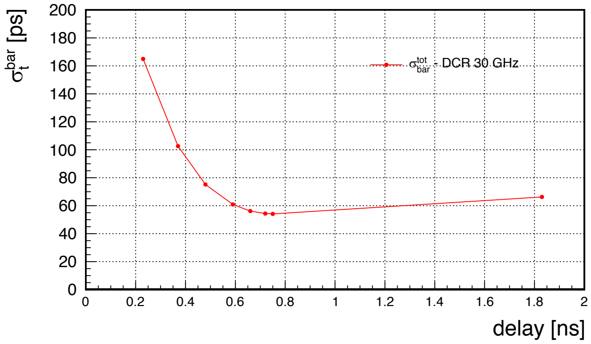

Fig. 8. Time resolution of LYSO pulses characteristic of EoL for DCR of 30 GHz as a function of the delay line in the DCR cancellation circuit.

Fig.8 shows the time resolution as a function of the delay in the DCR cancellation circuit for pulses with 6000 p.e. and SiPM gain of 1.5×10^5 and equivalent DCR of 30 GHz. In this measurement, the SiPM is operated at over-voltage of 1.5 V as foreseen at EoL to limit DCR. For the optimum setting of the delay line (700 ps), we obtain a resolution of 55 ps, in agreement with the simulation predictions.

V. RADIATION TEST

The tolerance to radiation of the previous version of the circuit (TOFHIR2A) is extensively studied including TID irradiation with x-rays and the measurement of Single Event Upset (SEU) rate in irradiation with heavy-ions [5]. In order to validate the tolerance to radiation of the revised front-end and discriminator, we measure the effect of ionizing radiation in TOFHIR2X using the X-ray irradiation facility at CERN. The maximum expected dose in the BTL is 2.9 Mrad (4.8 Mrad including the safety margin). We irradiate the ASIC up to 7 Mrad in steps of 0.5 and 1.0 Mrad. The irradiations are performed at -25ºC. Before irradiation (at 26 ºC), during irradiation at each step, and 15 hours after irradiation (annealing at room temperature), several measurements are performed. We measure the current consumption, the bandgap voltage, the front-end noise, the shape of the internal analog test pulse, and performed the TDC and QDC calibration in all TACs and QACs. The time interval between steps is of the order of 10 minutes preventing annealing effects.

As for TOFHIR2A [5], we observe effects due to the large leakage current at dose of ~1 Mrad reported for the technology TSCM 130 nm produced in Fab 14 [9]. The effects due to transistor leakage should not be visible in TSMC Fab 6, where the final chip production will be made, since the increase of leakage current at 1 Mrad in this Fab is ~100 times smaller than in Fab 14 [9].

On the other hand, we observe negligible or minor effects on the frontend amplifiers, TDC and QDC up to 7 Mrad. The only noticeable effect is a reduction of the pulse amplitude by ~6% after 7 Mrad, as it was already observed with TOFHIR2A. Within measurement uncertainties no other sizable effects are observed.

VI. CONCLUSIONS

The TOFHIR2X version of the readout chip for the CMS barrel MIP Timing Detector is developed. The measurements of time resolution with TOFHIR2X and BTL sensor modules match very well the simulation expectations. In particular the time resolution obtained under the EoL conditions, characterized by very large DCR, confirms the simulation expectation. A successful TID radiation test is performed.

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