Radiation tolerance of the TOFHIR2 chip for the CMS/CERN timing detector

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***Abstract*— The CMS detector is set to be upgraded for the HL-LHC proton collider at CERN with the addition of a MIP Timing Detector (MTD). The MTD will feature barrel and endcap timing layers, BTL and ETL, to enable precise timing measurements of charged particles. The BTL sensors utilize LYSO:Ce scintillation crystals coupled with SiPMs and TOFHIR2 ASICs for front-end readout. Over the HL-LHC's lifetime, the system is expected to achieve a timing resolution of 30-60 ps for MIP signals at a rate of 2.5 Mhit/s per channel. During its operation, the detector is exposed to a large flux of particles. In consequence, the TOFHIR2 chip must be resistant to the expected total ionization dose TID (29 kGray) and to the integrated particle fluence (2×1014 neq/cm2) in the BTL.**

In this paper, we present an overview of the TOFHIR2 requirements and design, and of the measurements performed with TOFHIR2 ASICs with emphasis on the radiation resistance. The measurements of TOFHIR2 associated to sensor modules were performed in different test setups using internal test pulses or blue and UV laser pulses emulating the signals expected in the experiment. Extensive radiation tests, including x-rays and heavy ions, confirmed that TOFHIR2 remains unaffected by the radiation environment throughout the experiment's lifetime.

I. INTRODUCTION

The CMS experiment at CERN is being upgraded for the High-Luminosity Large Hadron Collider (HL-LHC), including the development of a new MIP Timing Detector (MTD) for precise timing measurements of charged particles [1, 2].

The Barrel Timing Layer (BTL), a cylindrical detector with an active area of ~38 m², utilizes LYSO:Ce scintillating crystals coupled with silicon photomultipliers (SiPMs). Each detector cell consists of a 3.0×3.75×54.7 mm³ crystal bar, with two ~3.0×3.0 mm² SiPMs at either end. The SiPM signals are processed by the TOFHIR2 ASIC, and the full BTL detector comprises 331,776 electronic channels [3, 4].
LYSO:Ce offers high density (7.1 g/cm³), a large light yield (~40,000 photons/MeV), and a 40 ns scintillation decay time. Charged particles deposit ~4.2 MeV in the crystal, generating scintillation light detected by SiPMs. Each SiPM contains 14,400 microcells (25×25 µm²), with a photon detection efficiency of 20-55% at 420 nm and gain in the range $2.9–9.7\times10^5$. The SiPM current pulse has a 30 ns peaking time and a 200 ns decay tail.
During HL-LHC operation, the detector will be exposed to high radiation levels, reaching 2×10^{14} neq/cm², leading to SiPM degradation and an increase in Dark Count Rate (DCR) from 0.5 MHz to 10-20 GHz. To mitigate noise, SiPMs will be cooled to -45°C and periodically annealed at 60°C.

The TOFHIR2 circuit must be radiation hardened to the expected total ionization dose TID (2.9 Mrad) and to the integrated particle fluence (2×10^{14} n_{eq}/cm^2) in the BTL.
TOFHIR2 is chip designed by PETsys Electronics [5], using CMOS 130 nm technology and manufactured in the same foundry where the HEP community is producing ASICs for the HL-LHC upgrades. It is based in a PETsys Electronics chip originally designed for PET applications [6]. Detailed circuit analysis and results can be found in previous publications [7-10].

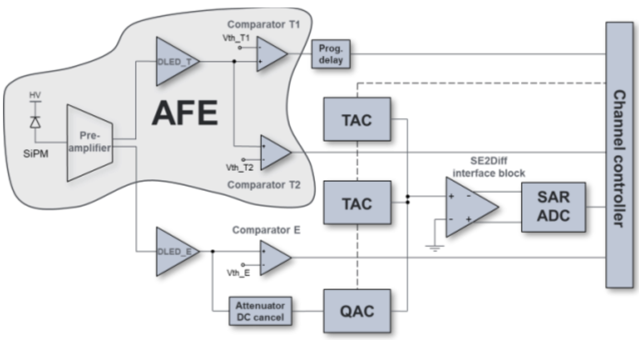

Fig.1 – TOFHIR2 Channel.

The ASIC features 32 independent channels (one channel architecture is shown in fig. 1), each with an analog front-end, digitizers, and digital control. Each TOFHIR2 ASIC channel includes a pre-amplifier, two post-amplifiers (T and E), three discriminators (T1, T2, and E), two Time-to-Amplitude Converters (TAC), a Charge-to-Amplitude Converter (QAC), a 40 MHz 10-bit SAR ADC, and local control logic. TACs and QACs are replicated eight times to manage Poisson fluctuations in event rate. The pre-amplifier provides a low-impedance input, splitting the current into timing, energy discrimination, and charge integration branches. Post-amplifiers incorporate pulse filtering to improve time resolution. An analog test pulse generator is included for testing.

II. Radiation Tests

A. *TID Radiation Tests*

TOFHIR2 prototypes were tested at CERN's X-ray irradiation facility (Fig. 2). The maximum expected dose in the barrel MTD is 2.9 Mrad. Two ASICs were irradiated: one up to 7 Mrad in 0.5 Mrad steps (Fig. 3) and another up to 3 Mrad in 1 Mrad steps. Measurements were taken between irradiation steps and after completion. The tests were conducted at -25°C. To prevent annealing effects, a 10-minute interval was maintained between steps. The same measurements were repeated 12 hours post-irradiation to evaluate annealing effects at room temperature. Additionally, time resolution with laser pulses was measured on the ASIC irradiated at 3 Mrad.

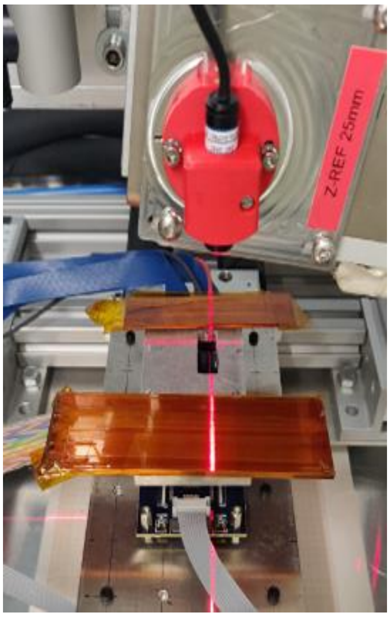

Fig. 2 - TID radiation tests at CERN.

It was observed some effects related to the significant leakage current at doses of approximately 1 Mrad. The current consumption at 1 Mrad is increased by 20%, followed by a decrease at higher doses. After 12 hours of annealing at room temperature the current consumption returns to the original value. Additionally, the increased leakage in NMOS transistors led to a 20% reduction in the DACs' voltage range at 1 Mrad.

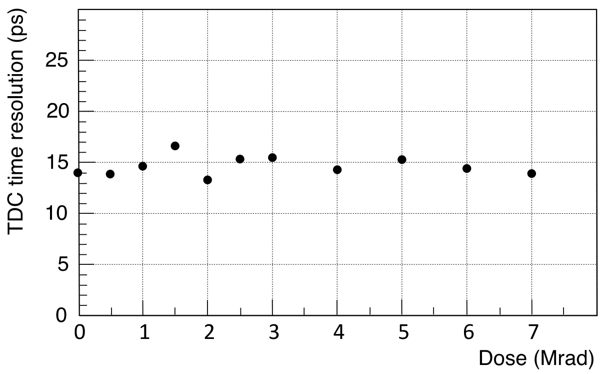

Fig. 3 - TDC time resolution as a function of TID measured with TOFHIR2 [10].

B. *SEE Radiation Tests*

SEE testing due to localized ionization in TOFHIR2 chips was conducted at the Heavy Ion Facility (HIF) in Louvain-la-Neuve (Fig. 4). To mitigate Single Event Effects (SEEs), TOFHIR2 employs Triple-Mode Redundancy (TMR), which triplicates flip-flops (FFs) and applies majority voting to configuration bits readout logic, and clock/reset trees. FF upsets are detected and corrected by the majority logic, with the total number of corrected errors recorded on the chip. Uncorrected errors may occur if a single particle alters the state of two out of three TMR flip-flops, which can be identified by reading back the configuration. Potential Single Event Transients (SETs) in the clock and resynchronization tree could lead to spurious chip resets or synchronization errors.

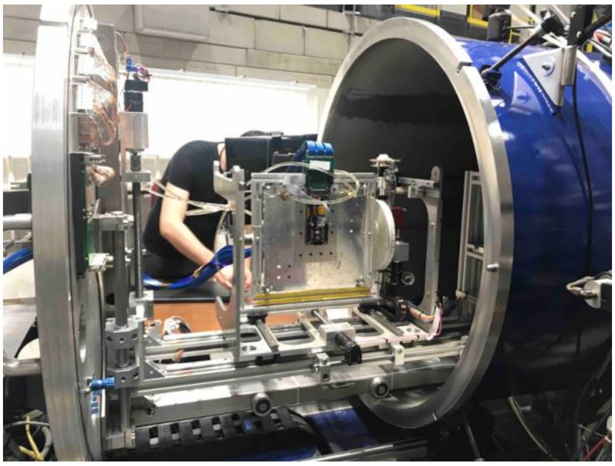

Fig. 4 - SEE radiation tests in Louvain-la-Neuve.

III. Conclusions

The TOFHIR2 readout chip for the CMS barrel MIP Timing Detector was successfully developed and tested. TID and SEE radiation tests confirmed its reliability. This critical component of the CMS timing detector was demonstrated to be both feasible and capable to be radiation hardened, as required in this string application, at CERN.

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