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Electrical measurement and read-out performance of a realistic, full-scale system bench of the CMS Inner Tracker Barrel for HL-LHC

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ABSTRACT: Due to the harsh environment of the High-Luminosity Phase of LHC, CMS will replace the present pixel detector with a new Inner Tracker implementing 65 nm CMOS read-out chips, CROC. The modules, i.e. the Inner Tracker subunits, are powered in series and read-out through a sophisticated opto-electrical chain. Full-scale systems are realized and tested for validation and performance assessment. The latest results obtained with a serial chain of the final prototype CROC modules for the barrel sub-detector will be presented. This system test also implements prototype mechanics and the final electrical opto-conversion stage. Results in terms of tuning, powering reliability and communication stability are presented.

KEYWORDS: Optical detector readout concepts; Particle tracking detectors

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1 The CMS Inner Tracker during HL-LHC

In the ultimate scenario, the instantaneous luminosity during HL-LHC will increase reaching up to $7.5\times10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, with the aim to collect up to $3000\,\mathrm{fb}^{-1}$ of integrated luminosity over 10 years. The CMS experiment [1, 2] will be upgraded to cope with such harsh environment. In particular the CMS detector [3] will be upgraded with a new tracker [4] designed to maintain unchanged the tracking performance by increasing the granularity and designed to withstand an unprecedented level of radiations, especially in the innermost layers. The system closest to the beam pipe is called the Inner Tracker, IT, and it will be equipped with thin, radiation resistant silicon pixel sensors, designed with a $25\times100\,\mu\mathrm{m}^2$ pitch, matching the increase in granularity demanded for HL-LHC. The silicon sensors are bump-bonded with the CMS Read-Out Chip (CROC), an ASIC based on 65 nm CMOS technology that has been prototyped by the RD53 collaboration [5], designed to be radiation tolerant and capable of operating at low thresholds. The IT will be equipped with modules that feature either four CROCs, named '2×2' or 'quad' modules, or two CROCs, referred to as '2×1' or 'double' modules, bump-bonded with the sensors. As shown in figure 1 the IT is divided into three subsystems: four barrel layers, TBPX, four disks per endcap, TEPX and eight smaller disks for each forward region, TFPX. The focus of this work will be on TBPX.

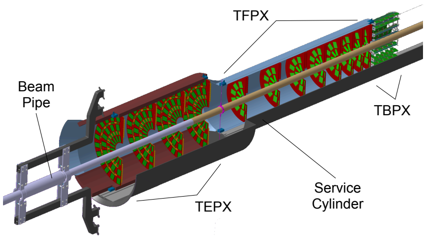

Figure 1. A schematic view of a quarter of the future inner tracker for HL-LHC, with the three subsystems highlighted.

A key feature of the whole IT is the powering scheme deployed to provide the needed 50 kW. This consists in serially powered chains of up to 12 modules, where all the chain elements receive the same current [6]. This scheme, sketched in figure 2(a), is radiation resistant while ensuring also a reduction of the tracker's material budget. It is implemented in the modules thanks to a built-in component of the CROC, the ShuntLow-Drop-Out (ShuntLDO) power regulator. Two components form the ShuntLDO: a current shunt that guarantees a constant current consumption of the CROC, regardless the operations the ROC is performing and a Low Drop-Out voltage regulator which ensures

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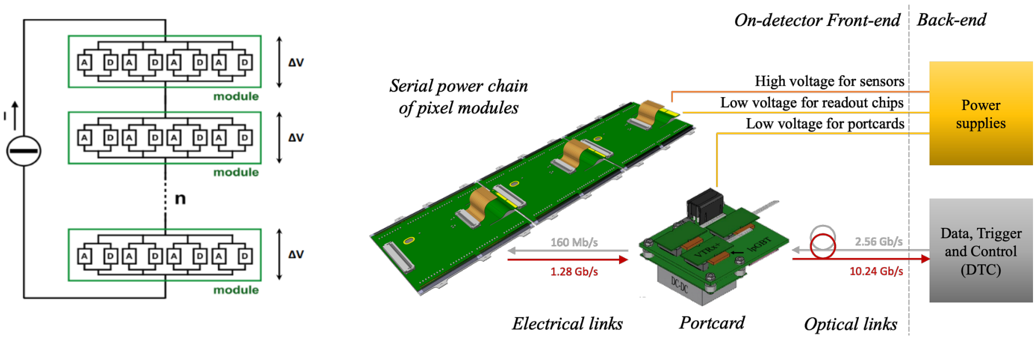
the required 1.2 V locally to the analog and digital domains. The serial chain is operated with extra current, the ‘headroom’, that is consumed by the shunt. The combined action of the ShuntLDO results in a resistor-like behaviour with constant current consumption.



(a) (b)

Figure 2. The scheme for a serial power chain of multiple modules (a) and a schematic view of the final read-out chain with electrical links and opto-electronic conversion board (b).

A passive high density interconnect (HDI) circuit is wire-bonded to the CROC flip-chipped to sensors in the modules, providing the data read-out and power connectors. A thermal layer called cooling plate is glued to the module to help mechanical fixation to the ladder structure while favoring module heat removal. The mechanical structure of the ladder, where the modules are attached with screws and thermal grease, is manufactured in thin carbon fiber and carbon foam and hosts the stainless steel pipes where the CO_2 evaporative cooling flows at $-35°$ C.

The read-out chain, shown in figure 2(b), has been optimized to further reduce the passive material and features ‘e-links’, ‘portcards’ [7] and optical fibers down to the far-end electronics. The e-link is a bundle of AWG 36 twisted pairs that connect the module to the opto-electronic conversion board, the portcard, with one command lane common for all the CROC of the module and up to six high speed data lanes. The portcard hosts three low power GigaBit Transceiver chips, lpGBT [8], and three Versatile Link Rx+ VTRx+ [9] to convert the electric signal into optical. Optical fibers grouped in a fan-out, ‘octopus’, bring the optical signal to the ATCA-boards [10] used as DTC (Data, Trigger and Control).

A realistic system bench of TBPX featuring full-scale ROCs and modules powered in series, several mechanical final elements and the final read-out chain is assembled at CERN [11]. First the set-up and power studies of TBPX serial chain will be discussed in section 2 and later the implementation of the read-out chain will be covered in section 3.

2 Implementation of TBPX system test

Eight ‘digital’ quad modules (without sensors) equipped with CROC-v1 were assembled in ETH Zurich with the cooling plate glued. The modules populated a TPBX ladder prototyped by INFN with four modules for each ladder, fixated only with screws and without thermal grease to ease a possible replacement. The modules are powered in series thanks to two custom adapters connected with the first two modules of each ladder, realizing a chain of eight modules that loops over the first four modules and subsequently over the other four. The stainless steel pipe is connected to the CO_2 unit, with the CO_2 unit’s temperature that ranges between 20 °C and −35 °C. In this first

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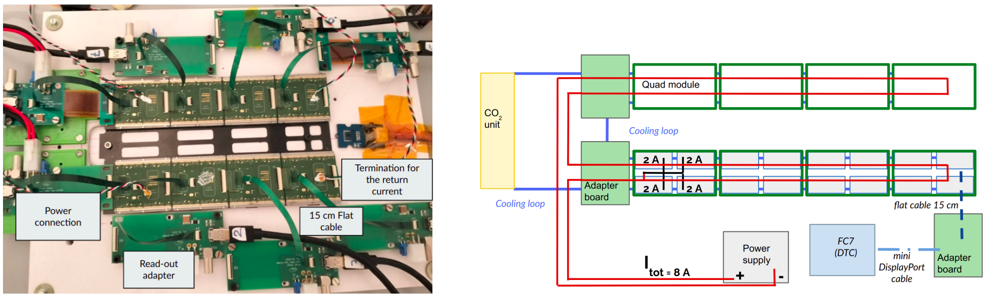
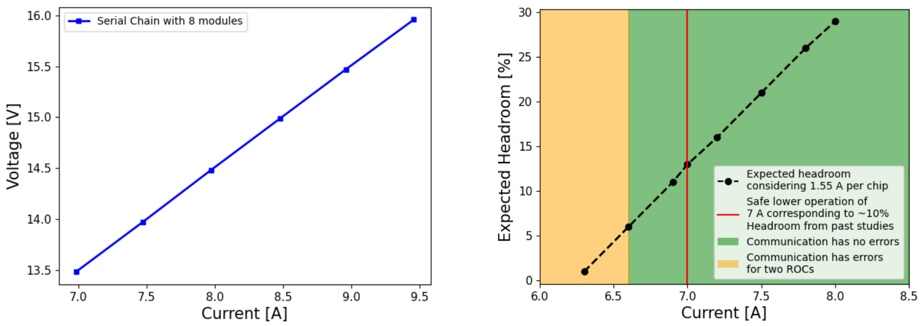
implementation the read-out chain is purely electrical, formed by 15 cm flat cable, a custom adapter with a mini-DisplayPort connection to the FC7 [12], which is a μTCA compatible AMC based on FPGA and used here for DTC application. The set-up is shown in figure 3.



(a) (b)

Figure 3. The set-up for the TBPX system test at CERN, which features 8 quad modules mounted in the prototype mechanical structure and read-out with a purely electrical chain in (a). In (b) a schematic of the serial chain powering and read-out chain and the cooling loop.

The serial chain is powered with different input current showing a steady resistor-like behaviour up to 9.5 A, as it is shown in figure 4(a). Higher current values were not probed to avoid an unnecessary thermal stress for the modules. With a current of 8 A each module requires 1.7 V, as it happens for stand-alone module measurement. The nominal value for powering will be set between 7.5 to 8 A, in order to provide the needed headroom to the shunt. The expected headroom is investigated as a function of the input current, showing stable behaviour and the chain fully operable down to 10% headroom safe operation limit [13], as expected. The measurement was repeated for different temperatures, with unchanged performance. The results at -10° C are shown in figure 4(b).



(a) (b)

Figure 4. The input current and the required voltage for the eight modules chain (a). (b) The headroom as a function of the input current at -10° C. Even though the serial chain has been powered with lower values, this does not guarantee a sufficient margin for the headroom, and the stability target remains 10% headroom [13].

The 31 CROC that were effective communicating from the 8 modules were also tuned to a threshold of around 1100 e^{-} [11], while being powered with a current of 8 A and CO_2 cooled at -31° C. This is the operational threshold for non-irradiated modules. The noise measured is below 90 e^{-} and the threshold width is around 50 e^{-}. The results are fully compatible with the ones obtained for a similar threshold in a module stand-alone measurement, being unaffected by the serial powering chain and the cooling, i.e. the configuration foreseen in the final experiment. Maximum two CROCs failure in the same module can be absorbed by the ShuntLDO operations. A test with a module with a power failure for a single ROC has been also performed, with the global powering performance of the serial chain unaffected.

3 Results with the final optical read-out chain

The final read-out chain is implemented through two portcards with three lpGBT-v1 each and e-links with 1.6 m and 1 m length. The e-links, manufactured by Kansas University, feature flexible paddle boards to facilitate the insertion in the dedicated portcard connector, and are formed only by four data links, one for each ROC of the TBPX quad module. Five 1.6 m long e-links have been added, this being the final length for TBPX, and one 1 m long. A single module is connected to a lpGBT through one e-link. The portcards are powered in parallel as it will happen in the final experiment and they are mounted on the mechanical structure that will host them in the service cylinder, the cartridge. The updated set-up is shown in figure 5.

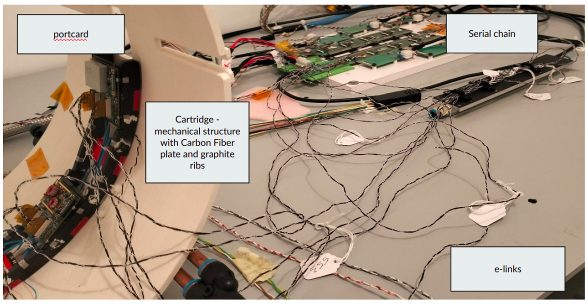
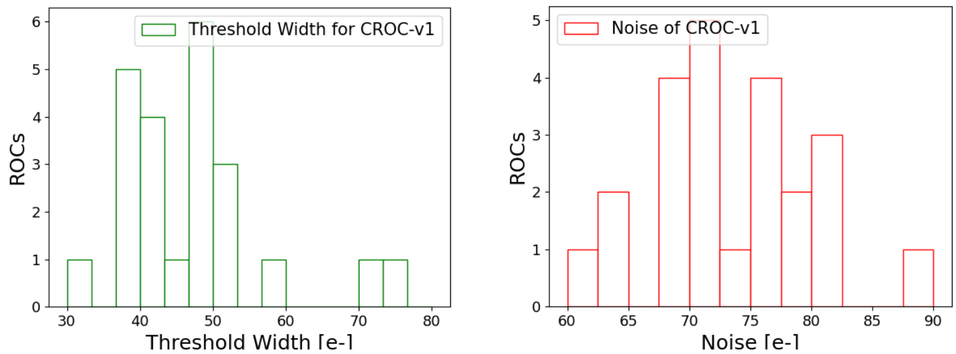


Figure 5. The set-up with the final read-out chain that features the two portcards with lpGBT-v1 and the e-links, from the modules to the portcards. An untested ROC is not communicating, resulting in 23 ROCs in total.

To evaluate the effect of the read-out chain the six modules were tuned targeting a threshold around 1100 e^-. The threshold width and the noise, displayed in figure 6(a) and in figure 6(b), respectively, show low threshold width and low noise, being compatible with the measurement obtained with a purely electrical read-out and in standalone measurement.



(a) (b)

Figure 6. The threshold width (a) and the noise (b) for the CROCs belonging to the six modules tuned together with the final read-out chain prototype, showing unaltered performance from electrical read-out or standalone measurement.

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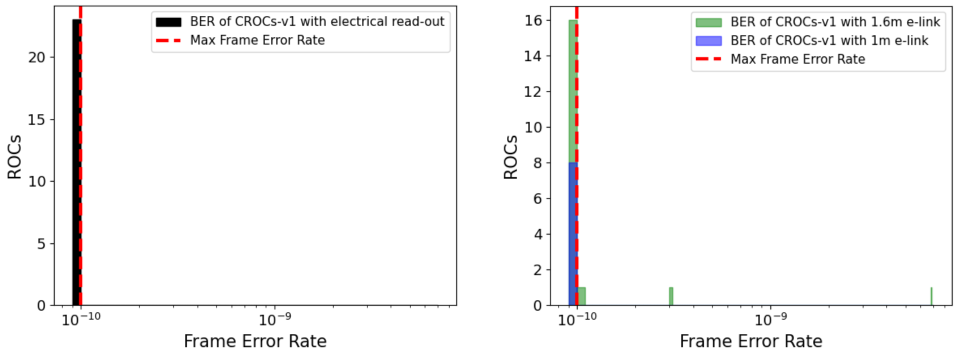
The communication performance of the new read-out chain is measured performing BER test, sending 10^{10} packages of 32 bits, called 'frames', and logging how many errors are retrieved. For CROC a Current Mode Logic Driver with three tap pre-emphasis is implemented: 'TAP_0' allows to modify the signal driver without deploying the pre-emphasis that can be addressed with 'TAP_1' and 'TAP_2', each adjustable with a 10-bits registry. The results of the BER test are shown in figure 7(a) for the purely electrical read-out and for the final read-out chain in figure 7(b). In the latter case the pre-emphasis was deployed for three ROCs, since they were failing employing TAP_0 only. The results with the final read-out chain are satisfying having only 3 ROCs plus e-link out of 27 failing the BER with marginal errors, caused by a bad quality e-link, acceptable in the e-links prototype. TAP_0 alone means no pre-emphasis and its default value, used also in the aforementioned test, is 900. The BER stability as a function of TAP_0 is investigated in figure 8 showing steady performance down to TAP_0 $\approx$ 250. This result was confirmed by several e-link plus module combinations, resulting in good stability at low TAP_0 values and with consistent margin for a possible degraded signal.



(a) (b)

Figure 7. The BER results for the electrical read-out (a) and for the optical read-out using e-links of two different lengths (b). The maximum rate corresponds to the maximum number of frames sent in this test.

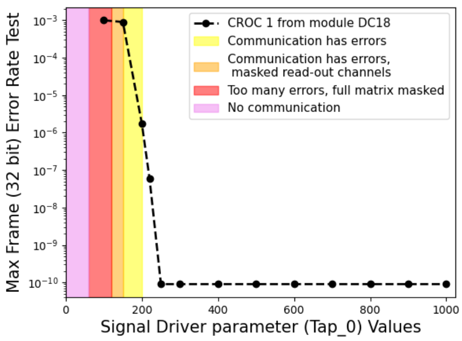


Figure 8. The frame error rate and the communication stability as a function of the driver strength parameter for one CROC read-out with one e-link of 1.6 m length.

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4 Summary and future perspective

The full-scale ROCs TBPX system test bench has proven reliable stability and satisfying results obtained with a realistic replica of the final experiment assembly. The communication performance is already encouraging and will be deepened with the final batch of e-links, targeting a higher number of frames sent. To achieve an even more realistic system bench, the final power supply prototype and modules equipped with sensors will be added.

Acknowledgments

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