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

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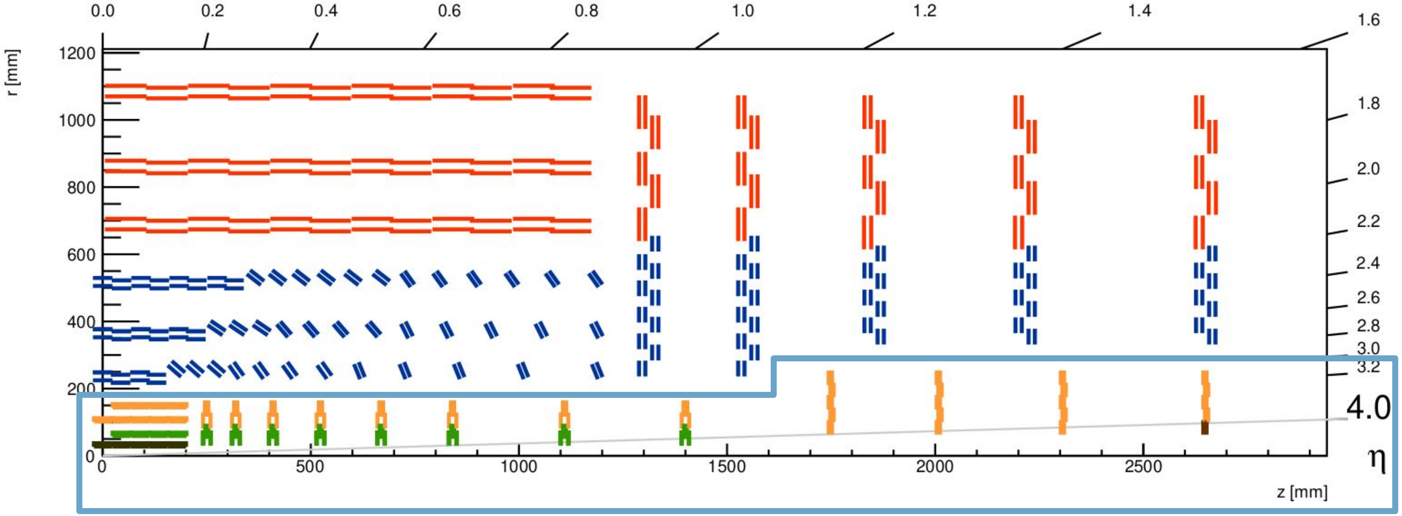
CMS Tracker during HL-LHC

- High Luminosity LHC (HL-LHC) will reach unprecedented values of instantaneous luminosity
  - CMS current Tracker won't survive with radiations damage foreseen during HL-LHC
  - Higher granularity is required to maintain tracking performance
- **CMS Tracker will be upgraded**

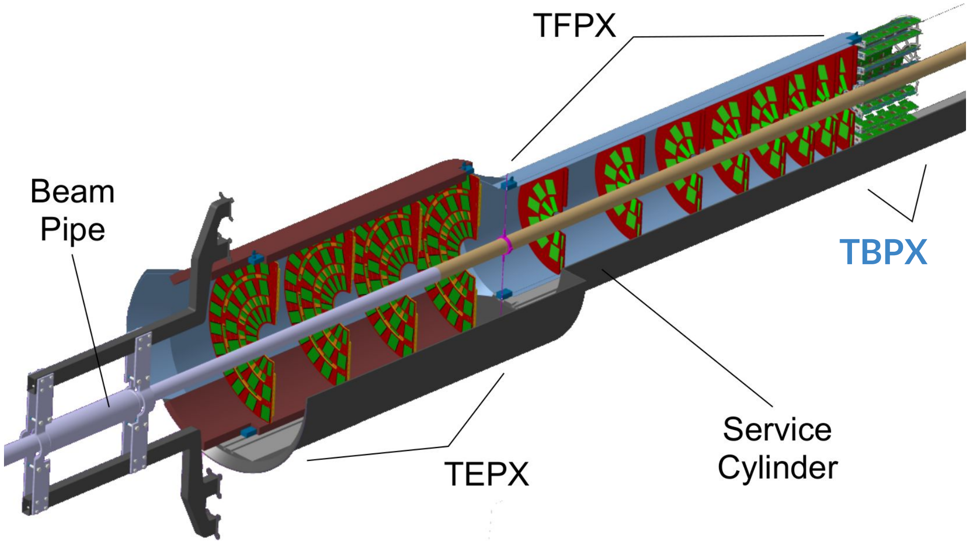
More on the Outer Tracker can be found in Ali, Georges and Patryk contributions



The CMS Tracker during HL-LHC, the focus of the talk will be only on the Inner Tracker IT

CMS Inner Tracker during HL-LHC

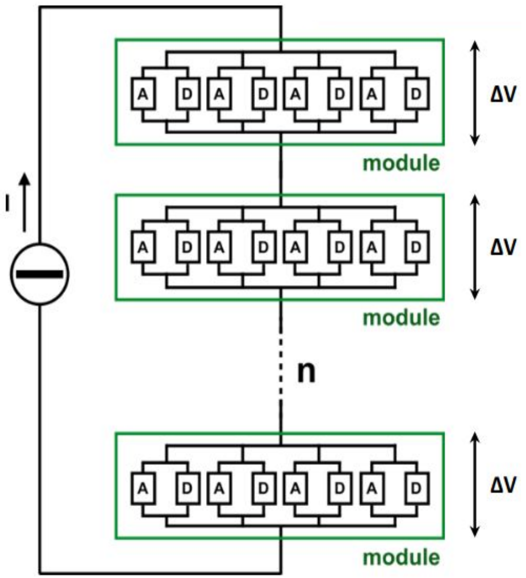
- Silicon Pixel sensors with 25×100 μm² pitch bump-bonded with CMS Read Out Chip (CROC) → High radiation tolerance
  - 4 ROCs and 1 sensor, quad module
  - 2 ROCS and 1 sensor, double module
- Modules powered in series thanks to the ShuntLDO → Reduced passive material
- Light Carbon Fiber mechanics → Reduced passive material
  - CO_2 evaporative cooling with T = - 35 °C
- Read-out with lightweight electrical links and optical fibers → Optimized to work with higher trigger bandwidth during HL-LHC



Check [Filip's poster] for the development in TEPX system test

CROC and serial powering

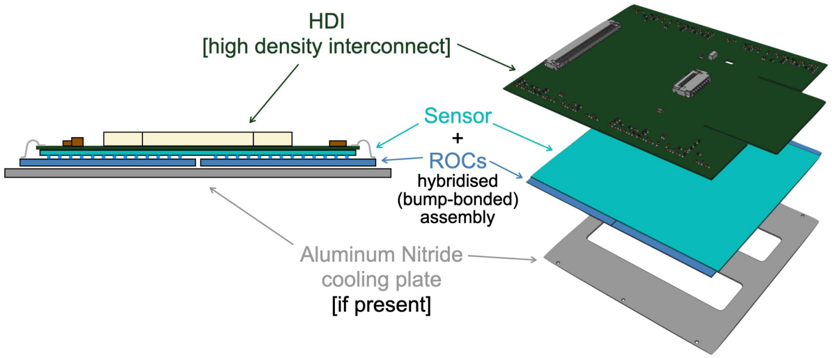
- CROC-v2 ASIC designed by RD53 Collaboration, based on 65 nm CMOS technology
  - 432×336 channels
  - Low Threshold, Low noise, Radiation Tolerant
- Two on-chip integrated ShuntLDOs powering Analog and Digital domains
  - LDO part provides V_{dd} = 1.2 V
  - Shunt part burns any current not used by CROC (headroom)
    - Important for the stable operation of SP
- Up to 12 modules powered in a serial chain
  - Constant current injected in a series of modules
  - Current shared among CROCs in the same module



TBPX Modules and mechanics

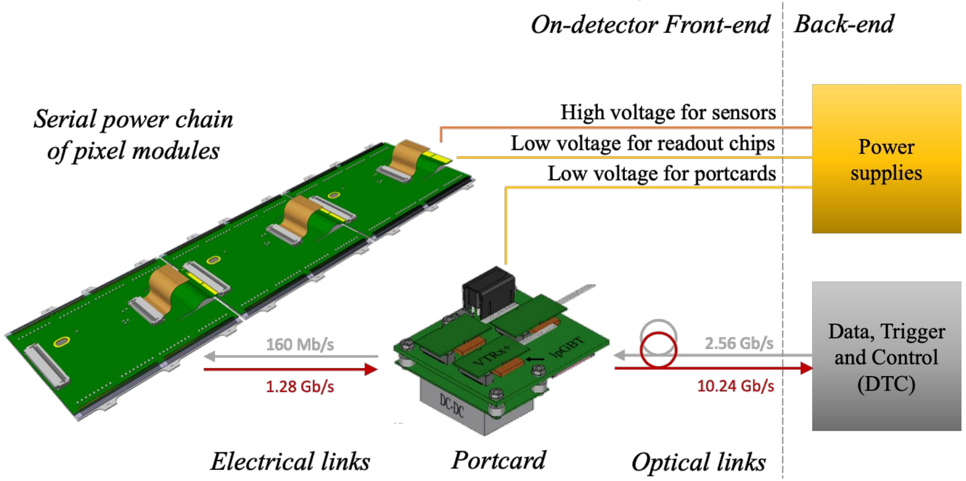
- HDI: passive circuit necessary for handling and power/read-out connections
  - 15 pins read-out connector in quad
  - Connection between modules to implement serial powering via flexible pigtail

- Cooling plate to increase thermal contact of the modules → attached with diamond doped glue
- Carbon fiber + carbon foam ladder structure with integrated thin stainless steel CO_2 cooling pipes
- Modules fixed to ladders with screws and thermal grease to improve the thermal interface



TBPX Optical read-out chain

- Electrical links (E-Links): bundles of AWG36 twisted pairs between the modules and the opto-conversion boards.
  - Up to 6x data links @1.28 Gbps per module
  - 1x command link @160 Mbps per module for clock, trigger and configuration
- Portcard: custom board that hosts 3x LpGBT with 3x Vtrx+
- Optical Fibers connected with a naked fan-out and optical cables to the back-end

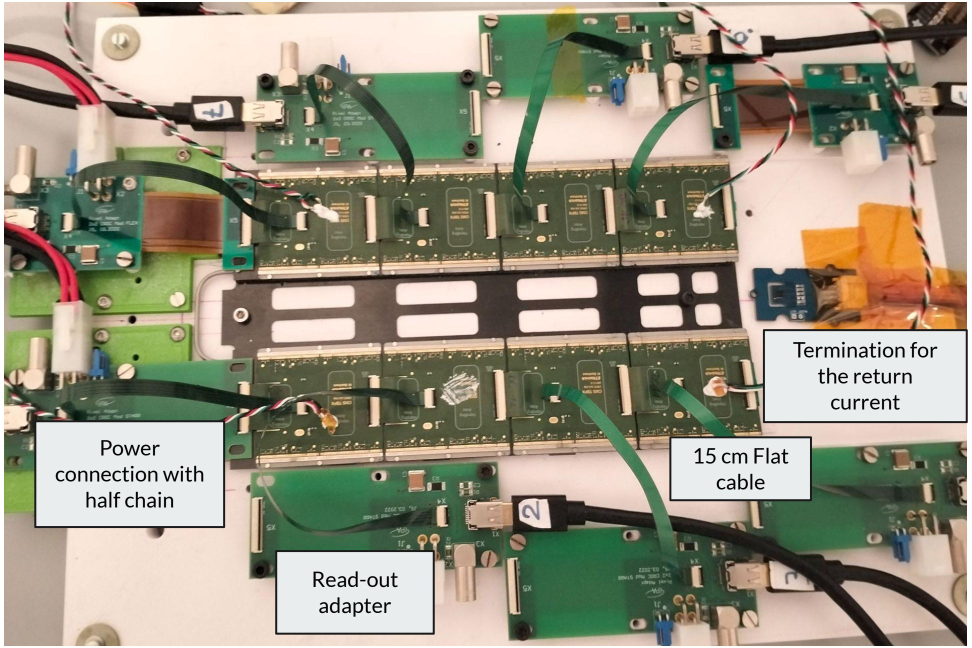


Implementation of the system test

- Serial chain of 8 digital (no sensors) quad modules with CROC-v1, assembled in ETHZ using diamond-doped glue and prototype cooling plate
  - 5x modules with tested ROCs and 3x modules with untested ROCs
- Prototypal TBPX L4 Carbon Fiber Ladder tested in Pisa, integrated at CERN with small screws (no thermal grease to ease potential replacement)
  - MARTA unit for bi-phase CO_2 cooling: from -35 ˚C to 20 ˚C
- Set-Up inside an isolated box operated @20 ˚C or @-10 ˚C with dry air
- Measurement will focus on electrical performance

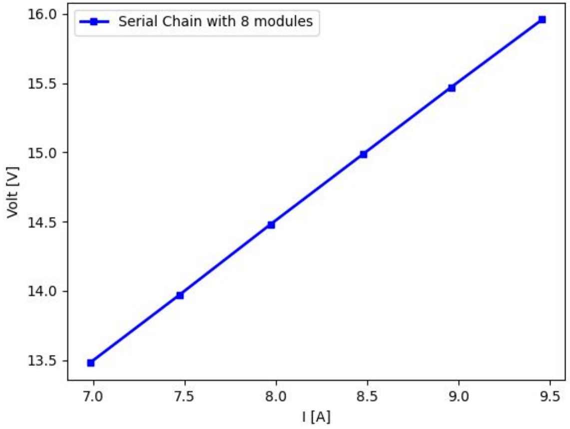
Set-up of the Electrical Read-Out test

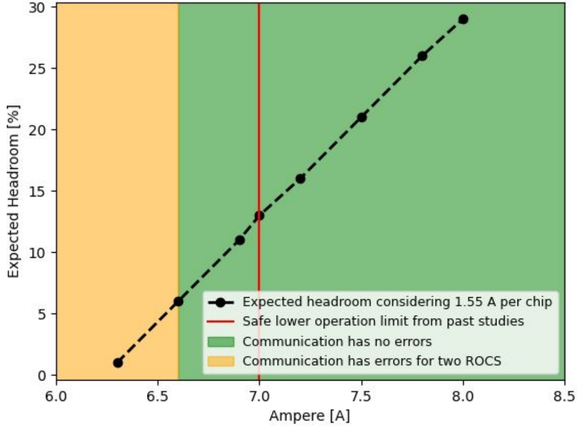
- Communication with 31 CROCs out of 32 in stand-alone module measurement
- FC7:
  - µTCA compatible AMC based on FPGA for DTC application
- Electrical read-out using 15 cm flat cable + custom adapter + mini-dp cable
- Adapter boards used for powering the first module of the ladders
  - Two ladders powered in series
  - No HV here (no sensors)



Power consumption studies

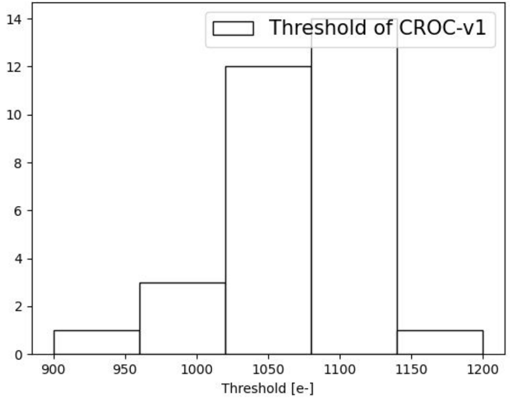
- With 8 Ampere each module requires ~1.7 V
  - Linear Resistor-like behaviour verified up to 9.5 A
- Power consumption with negligible differences between 10 ˚C and -32 ˚C, with stable communication in all the range
- Expect to operate the detector with 10% < headroom < 20%
- The expected headroom, estimated from simulation, is investigated as a function of the input current with different CO_2 temperatures
  - System proven to be stably operated down to 7 A (> 10% Headroom, considered the safe operability limit)
  - Communication stable for the majority of CROCs even below 7 A



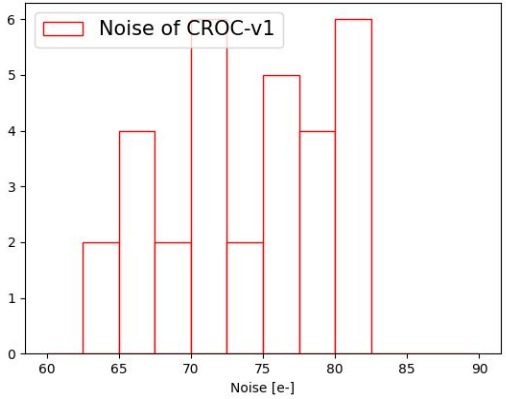


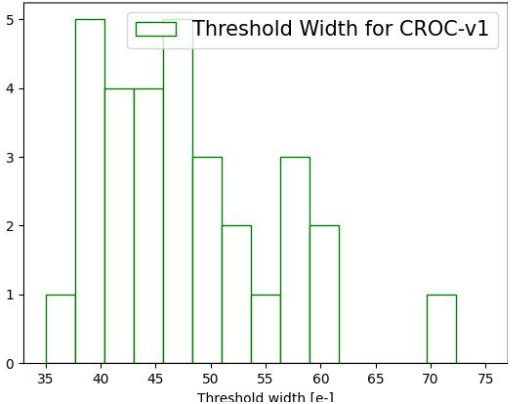
- 10 °C

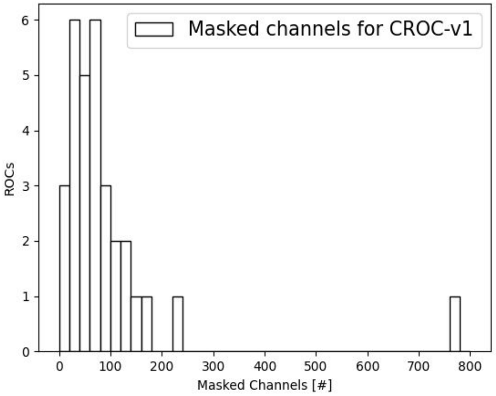
Tuning results with Electrical Read-Out



- CO_2 temperature at -32 ˚C
- 8 modules powered with 8 Ampere requiring 14.4 V
- All the 31 communicating CROCs were tuned targeting a threshold of ~ 1100 electrons
  - Average noise below 85 e-, Threshold dispersion below 75 e-, number of masked read-out channels <0.05%
- Results compatible with stand-alone measurements

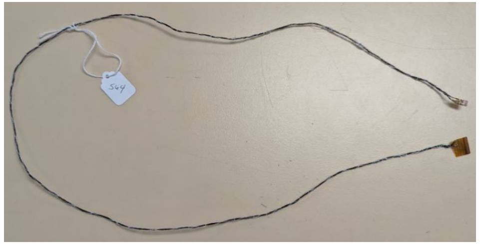




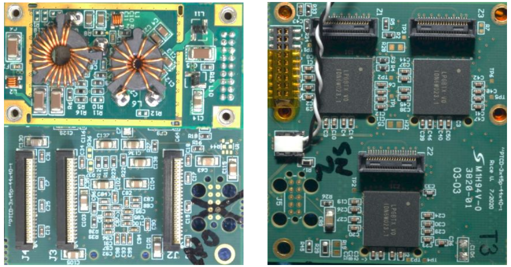


Optical chain prototype components

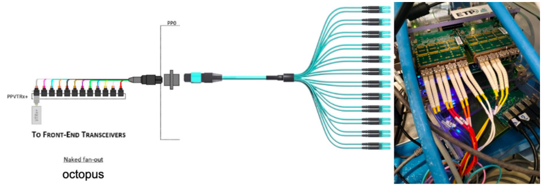
- TBPX quad e-links 4x up-link, each per ROC, 1x down-link, manufactured at the University of Kansas with length 1 m and 1.6 m
  - Flexible paddle-board for FFC connectors
- Portcards with LpGBT v1 powered with DC-DC mezzanine (bpol12V and bpol2V5)
  - Expected to work with V_{in} 8.5 V and 11.5 V
- Naked fanout optical cable to the FC7
  - Parallelization of up to 8x LpGBT and modules configured simultaneously from the back-end



E-links 15to45 pins



Portcard



12 MT connectors serving 12 optical channels, connected to (up to) 12 Vtrx+ MT with pins and spring clamps

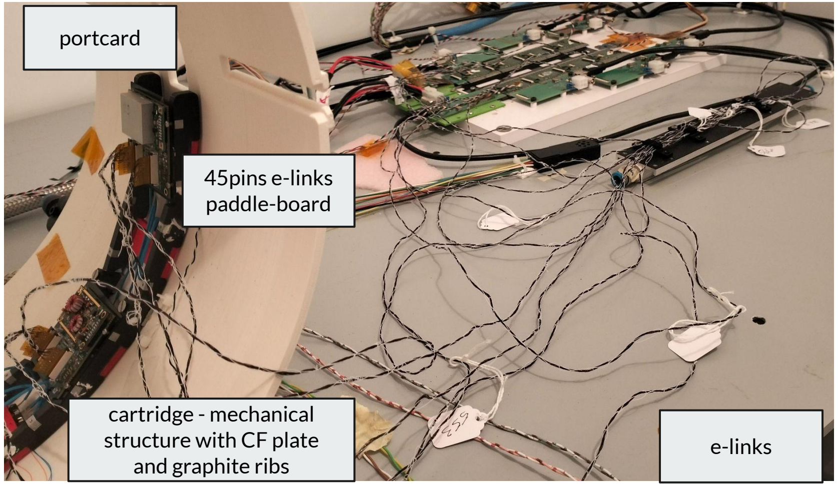
MTP/MPO connector with 12 optical channels

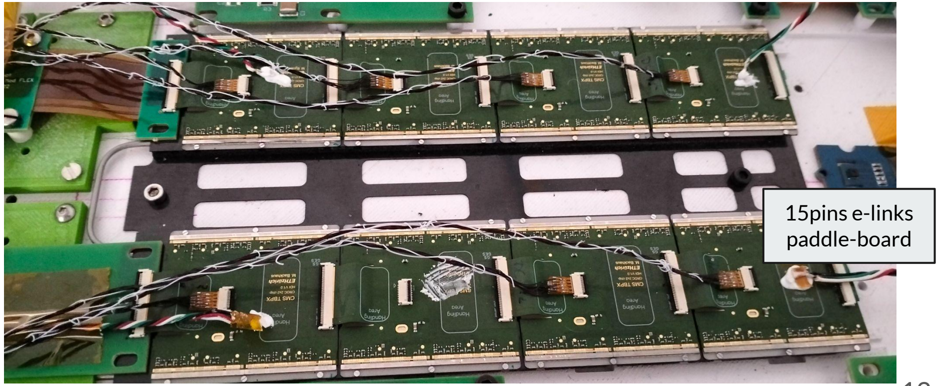
COTS MTP to LC Breakout cable to 12 optical channels

COTS SFP connectors mounted on two optical FMCs (COTS) on a FC7

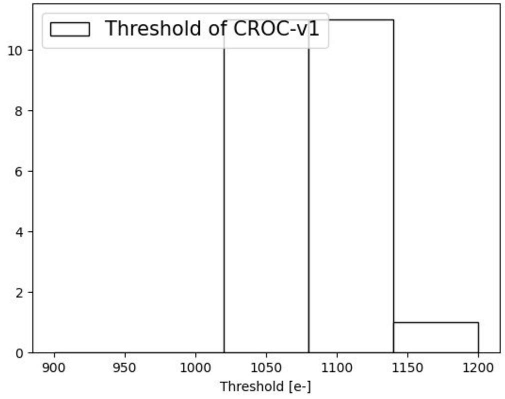
Set-up with optical read-out system-test

- 2x portcards powered in parallel and mounted on carbon fiber plate and on graphite ribs (cartridge) as in the final system
  - Verified that powering in parallel works - no start-up issues observed
- Each module connected to a LpGBT-v1
  - 5x 1.6 m e-links, 1x 1 m e-links
- 8x CROC-v1 modules powered with 7.5 A and 14 V at the Power Supply

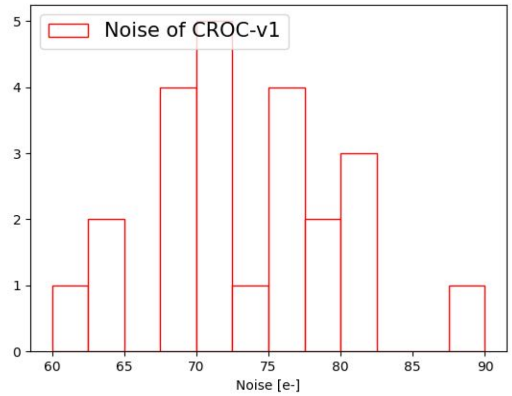


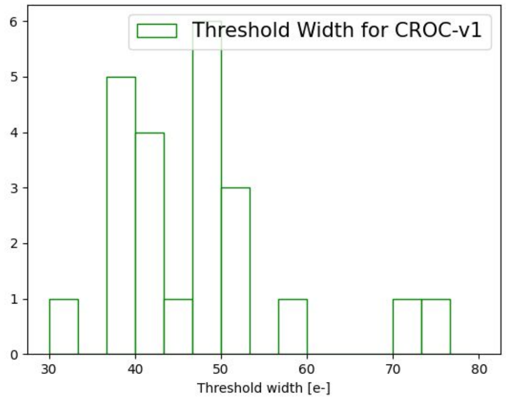


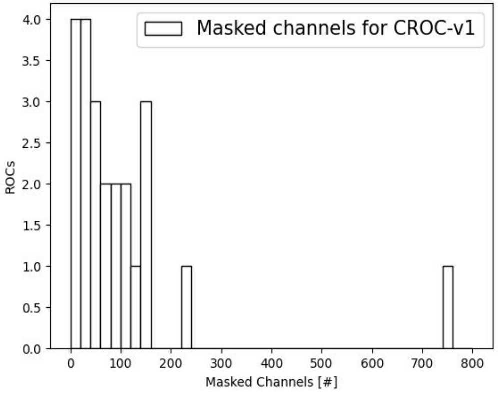
Tuning results with Optical Read-Out



- CO_2 temperature at -28 °C, reading only six modules
- All the 23 ROCs were tuned targeting a threshold of ~ 1100 electrons → one CROC excluded for communication issue
  - Further investigation → 1 up-link broken of 1.6 m e-link
- Results compatible with the one with Electrical Read-out
  - Average noise below 90 e-, Threshold dispersion below 75 e-, number of masked read-out channels <0.05%

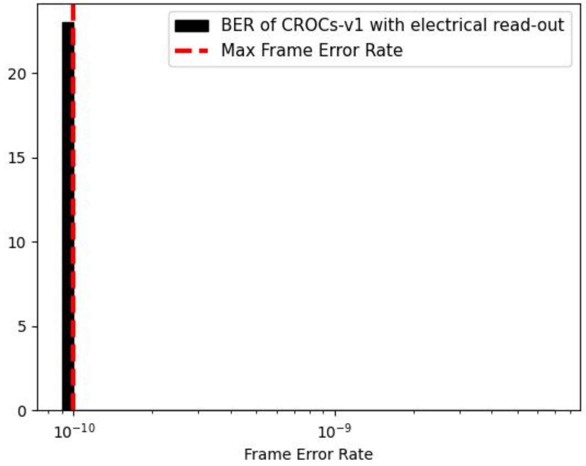




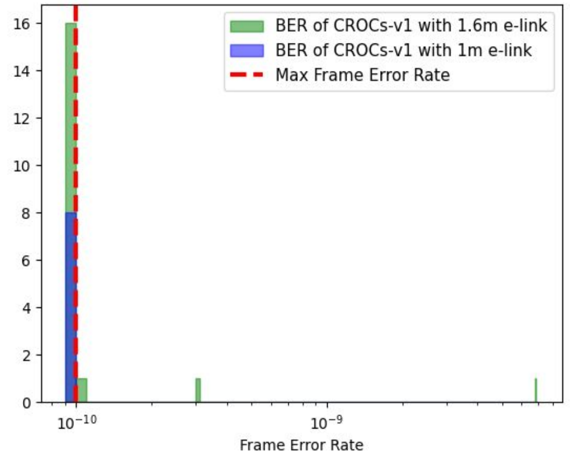


BER Test studies and comparison

- BER Test performed sending 10^{10} frames (32 bit each) at 1.28 Gbps: failing if errors are registered otherwise Frame Error Rate (FER) < 10^{-10}
  - The CROC CML driver strength can be adjusted with TAP_0 (default setting 900, TAP_0 only no pre-emphasis)
  - Programmable Pre-emphasis
- 27 CROC investigated: 3 ROCs only resulted failing BER Test with minimal errors
  - Deploying pre-emphasis to increase the performance of 3x CROCs
- Similar results obtained comparing with 6 modules read-out with electrical read-out only



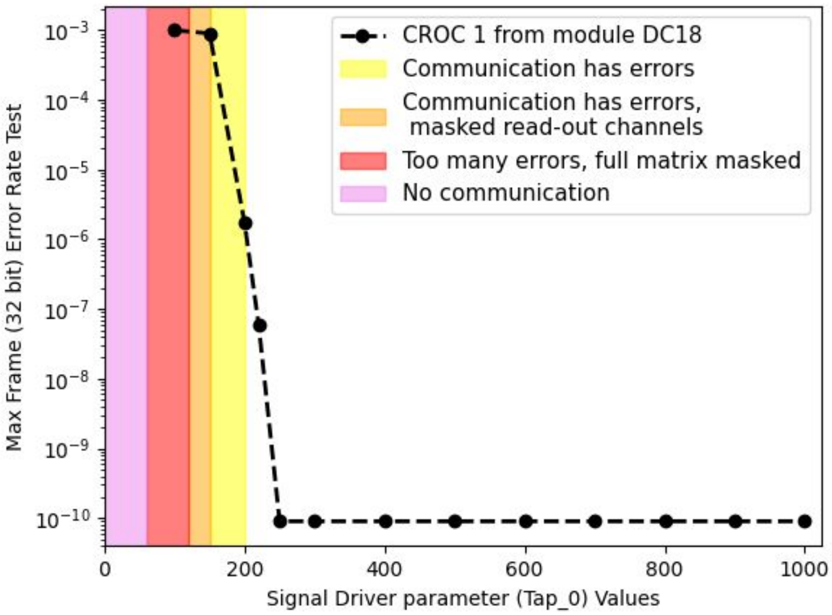
Electrical read-Out



Optical read-Out

BER Test vs signal driver

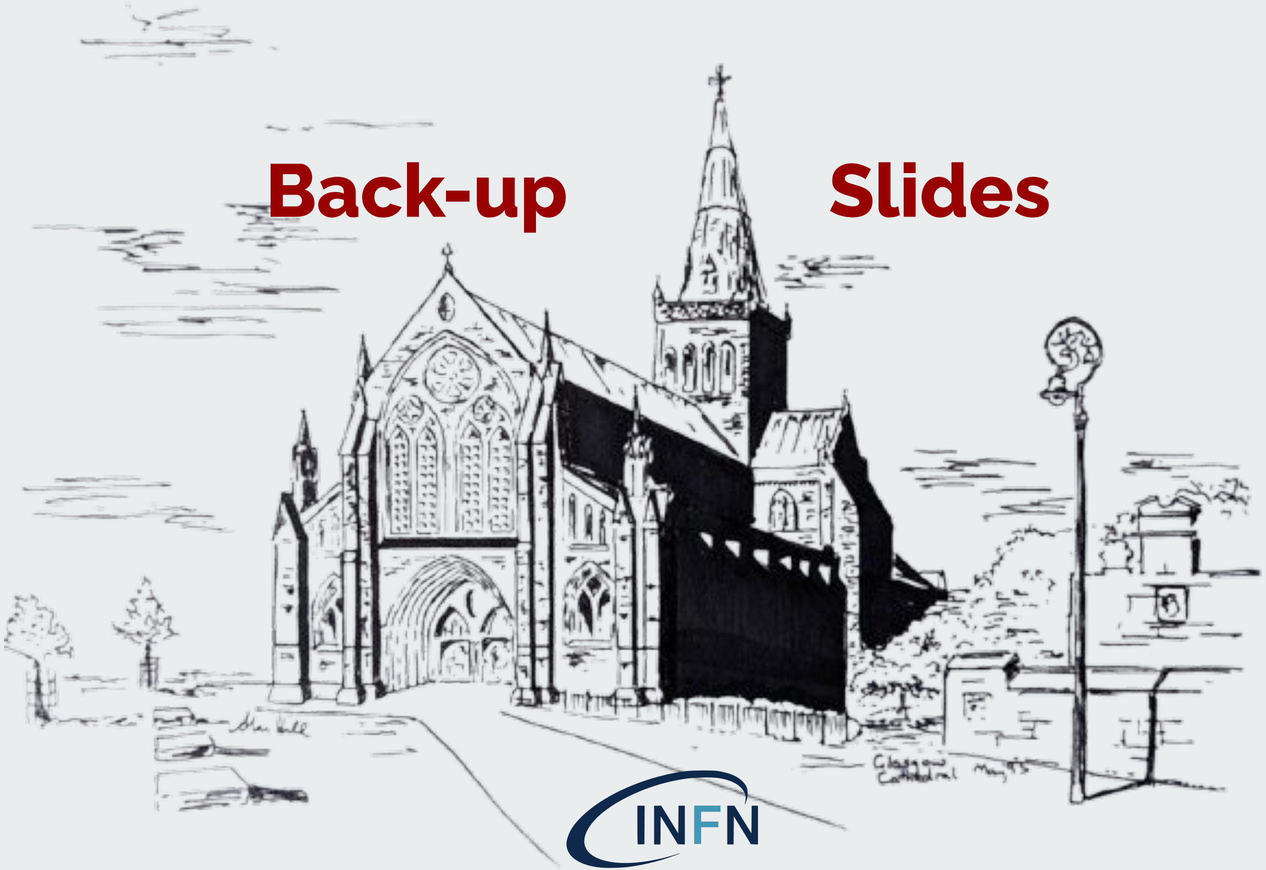
- Measuring number of noisy read-out channels and BER as a function of the signal driver
  - Using one 1.6 m e-link reading a single CROC sending always 10^{10} frames
  - Communication and noisy channels unchanged even at error rate ~ 10^{-7}
- Different combination of modules and e-links explored to grade both of them
  - Found 1x up-link broken of 1.6 m e-link
  - Most of the CROCs and E-links show no Bit error with signal driver ≳ 200 → large margin to cope with signal degradation



Summary and Future work

- TBPX 8 modules serial chain built and assembled at CERN from October 2023
- Final dimension read-out chip equips prototype quad modules mounted on mechanical prototype and read-out with the final read-out chain
  - Power studies confirm the robustness of the system
  - Optical read-out chain firstly assembled show similar properties to purely electrical read-out
- New tests with prototype e-links from company chosen to assembly TBPX e-links (instead of KU)
  - Repeat BER tests with longer target (results presented up to 10^{10} frames)
- Modules with sensors and power supply unit prototype will be added towards an even more realistic system bench of CMS IT

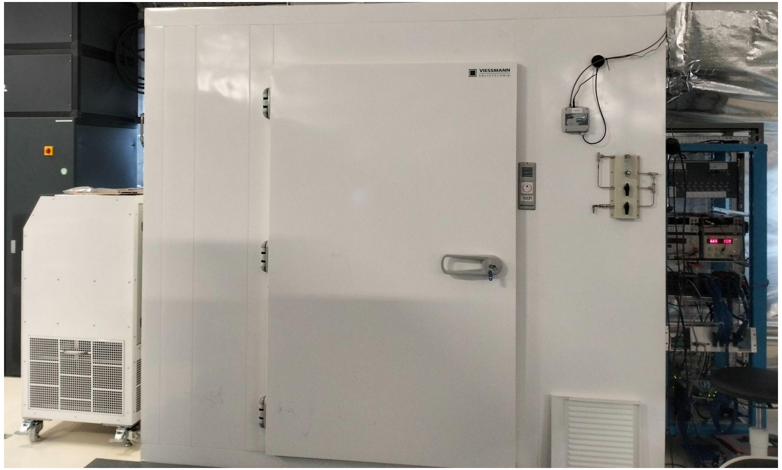
Back-up Slides



CROC-v2 main difference

- Same dimensions as CROC-v1
  - Submitted in October 2023
  - Wafer level testing ongoing
  - First single chip assembly produced
- Improved monitoring function
- SEU/SET Tolerance improved
- Data Merging possible issues fixed

CROC system test set-up

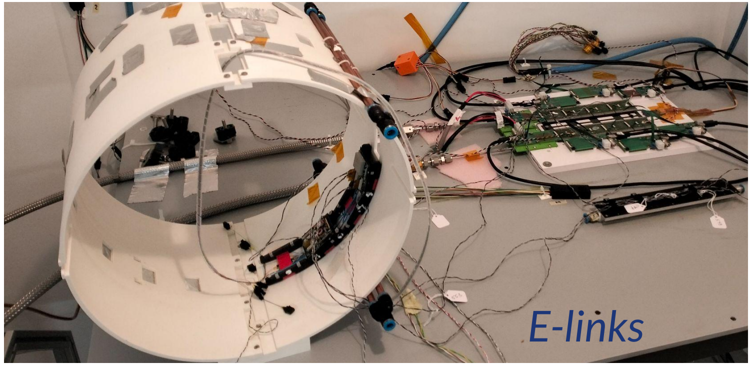


MARTA unit

Cold Box @20 °C or @-10 °C (not tunable)

Dry air:
Ambient temperature

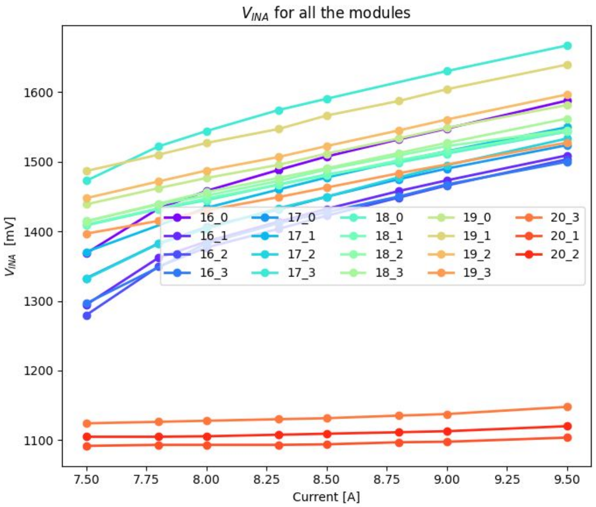
Rack with power supplies, FC7s and Interlock PLC



Mock-up cylinder with TBPX cartridge prototype

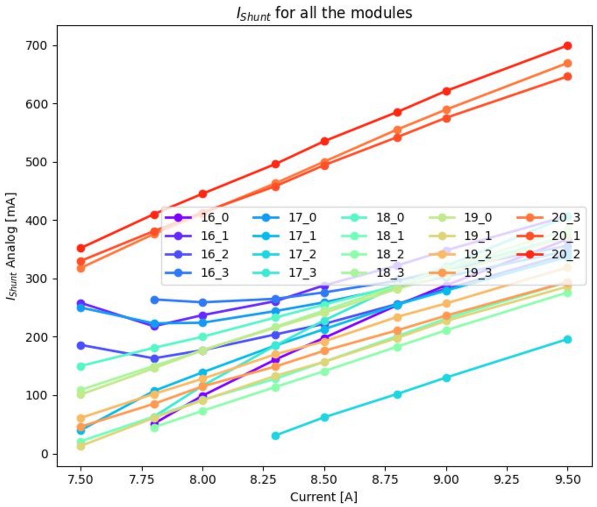
Failure scenario

- A module in the middle chain exhibiting a short-like behaving ROC
  - One CROC, 20_0, draws a lot of current but does not communicate
  - The other three CROCs results underpowered with no increasing input Voltage and with their shunts drawing excessive currents.
  - The performance of the rest of the chain are unchanged



Analog Input Voltage

Measurement from the monitoring
Focus only the relative scale, not the absolute one



Analog Shunt Current

Comparison between electrical and optical readout

- Some difference for the two tuning:
    - Electrical Read-Out tuning: Marta @-31 ˚C, modules at 8 Amp tuned between 1000 and 1200 e-
    - Optical Read-Out tuning: Marta @-27 ˚C, modules at 7.5 Amp tuned @ 1100 e-
- Similar results obtained in the two cases assuming a Gaussian Distribution

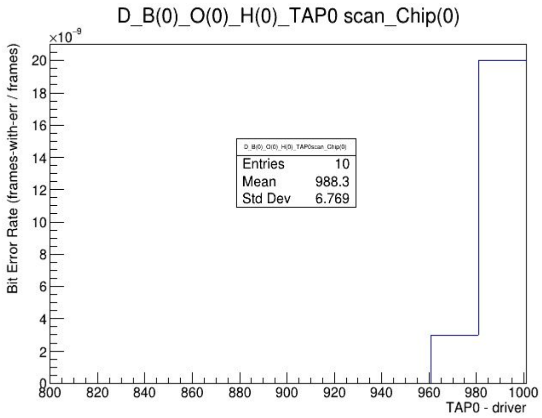
	Optical readout Mean	Optical readout Standard deviation	Electrical readout Mean	Electrical readout Standard deviation
Threshold [VCAL]	211	4	206	9
Width [VCAL]	9.4	1.9	9.6	1.7
Noise [VCAL]	15.5	1.1	15.6	1.1
Masked read-out Channels [#]	74	60	61	42

Tap_0 and Tap_1 optimization

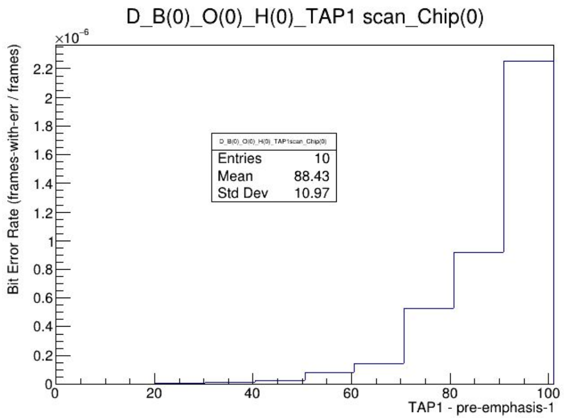
- Tap_0 (signal driver) and Tap_1 (undershoot) optimized in a 2D scan
- For the CROC not shown Tap_0 = 1000 (maximum value) and Tap_1 = 0 (no pre-emphasis)

Module and Roc	Tap_0 Value	Tap_1 Value
DC18 0	850	0
DC18 3	900	40
DC11 1	900	30
DC11 2	950	0

- 2x CROC optimized in standalone measurement passing the BER without errors
  - Show 10^{-9} FER in the collective BER reading out 6 modules



Tap_0 scan



Tap_1 scan