The new readout system for the Alice Zero Degree Calorimeters (ZDC) in LHC Run 3

TIPP 2023

05-09-2023

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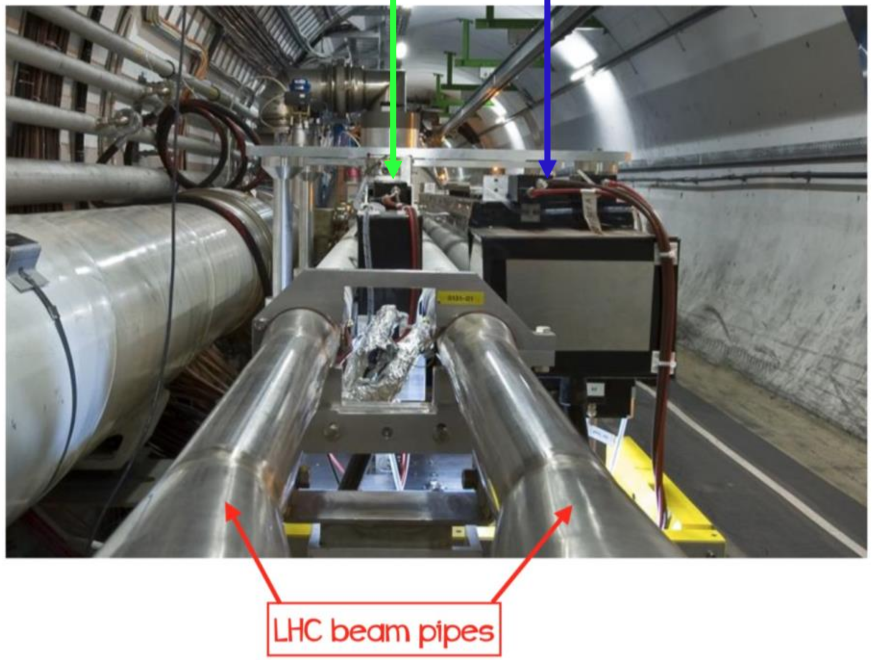
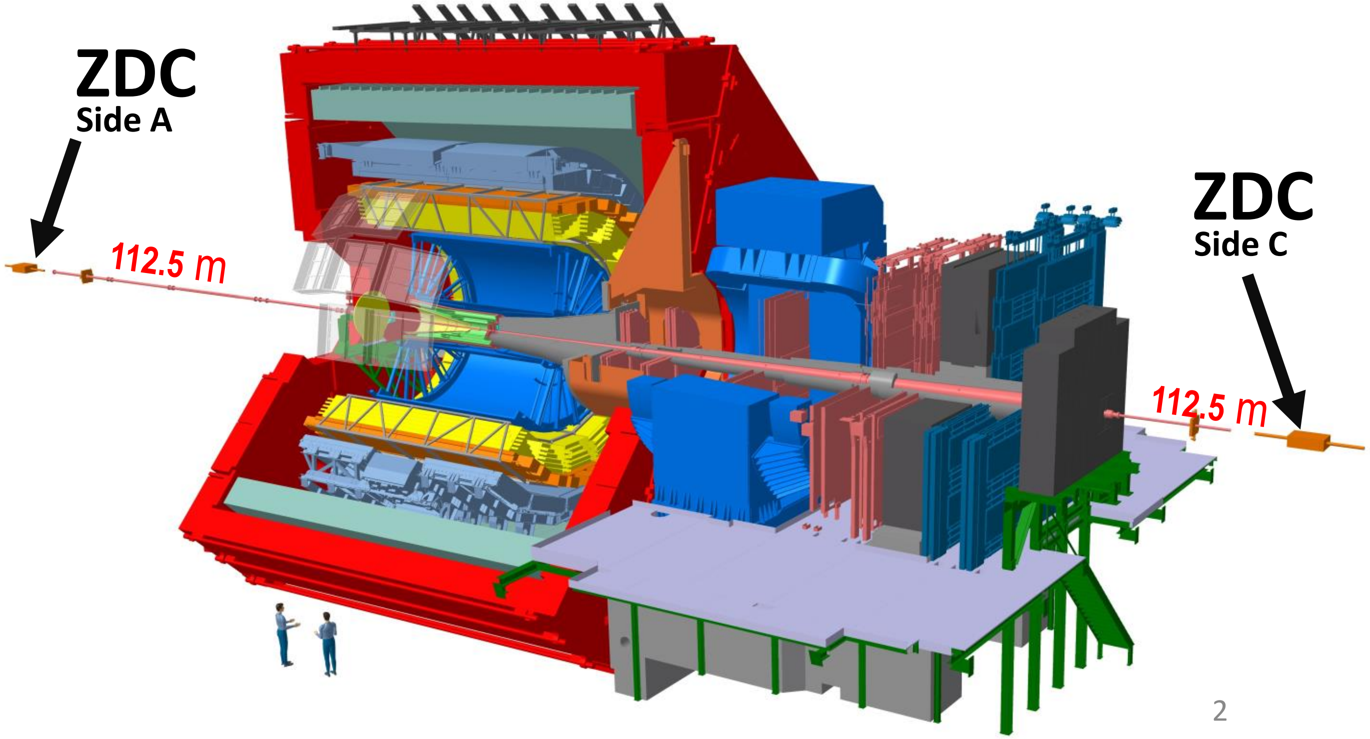
The ZDC in the ALICE experiment:

- The ZDC consists in two identical sets of calorimeters located on both sides relative to the interaction point IP2.
- Each set of detectors consists of a neutron (ZN) and a proton (ZP) calorimeter.
- Collisions may occur in fixed time slots named bunch crossings (BC) that are separated by ~25 ns.
- In A-A collisions, ZDC is mainly sensitive to spectator nucleons.
- The ZDC detector is completed by 2 forward EM calorimeters (ZEM) placed at about 7.35 m from IP2, on side A.

The ZN is placed at zero degree with respect to the LHC axis, between the two beam pipes.

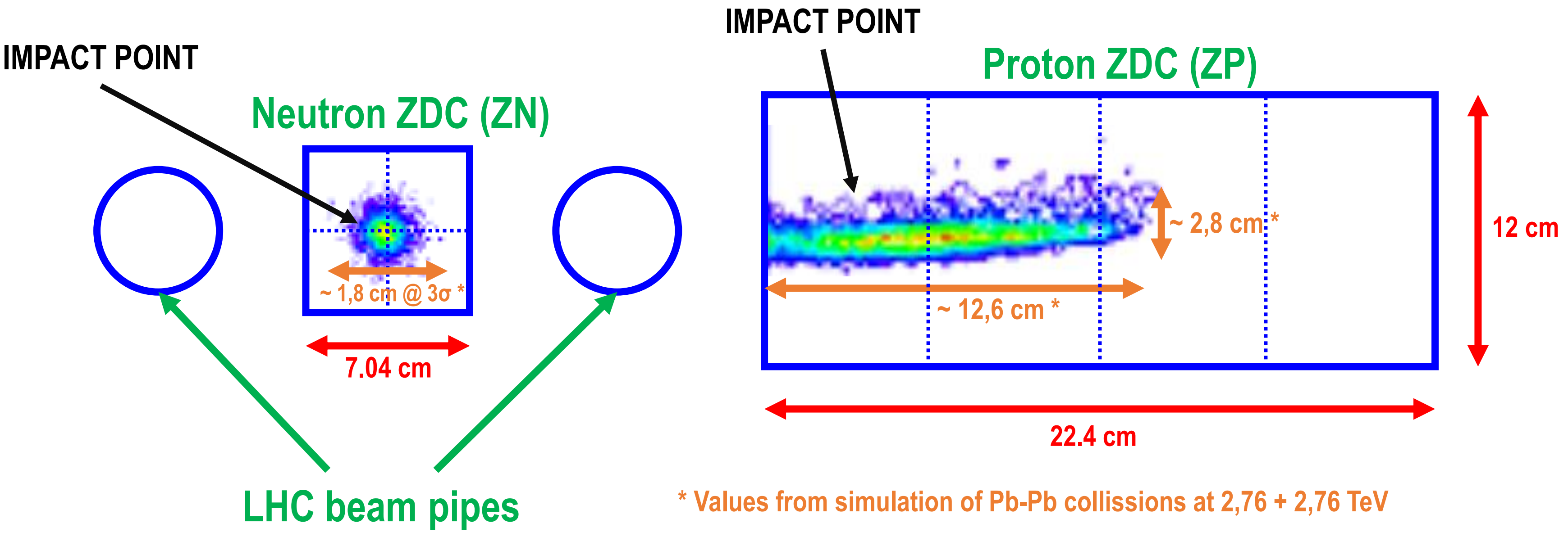
The ZP is positioned externally to the outgoing beam pipe.





The Zero Degree Calorimeters:

- The ZDCs are quartz-fiber spaghetti calorimeters with silica optical fibers as active material embedded in a dense absorber.
- The main purpose of these calorimeters is to provide a measurement of centrality in A-A and in p-A collisions and the luminosity in A-A collisions. In addition it provides an independent measurement of the time of the collision and the vertex position.



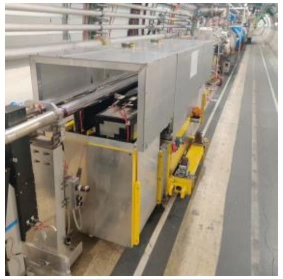
* Values from simulation of Pb-Pb collissions at 2,76 + 2,76 TeV

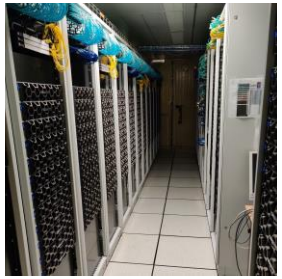
Run 3 requirements for ZDC readout:

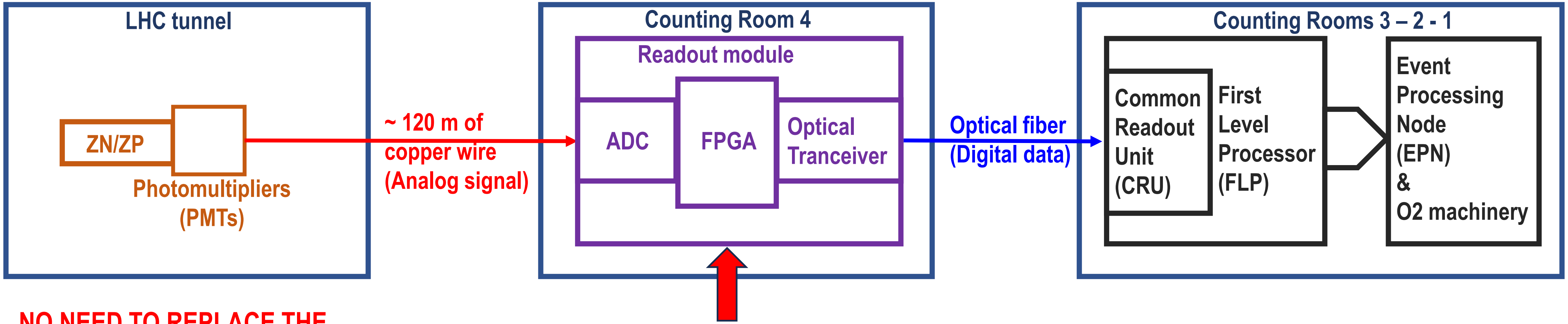
- Operation in self-triggered mode without dead time at an average event rate in Pb-Pb collisions of 2.5 MHz, due to hadronic + EMD processes.
- Preserve time and charge resolution performance of Run 2 (~20 % resolution for the single neutron peak and ~0.35 ns time resolution w.r.t. ALICE L0 trigger).
- Efficient triggering in the presence of a large signal dynamics (from a single neutron signal to ~60 neutrons for Pb-Pb collisions).
- Data acquisition with a bunch spacing of 50 ns (lower than the length of the signal of 60 ns).
- Firmware that evaluates the average baseline for each orbit in events where no collision takes place.
- Real time monitoring of the collision rate.

Run 3 upgrade strategy:

In order to exploit the potential offered by the increased luminosity in Run 3, the ALICE experiment upgraded its trigger and readout system.







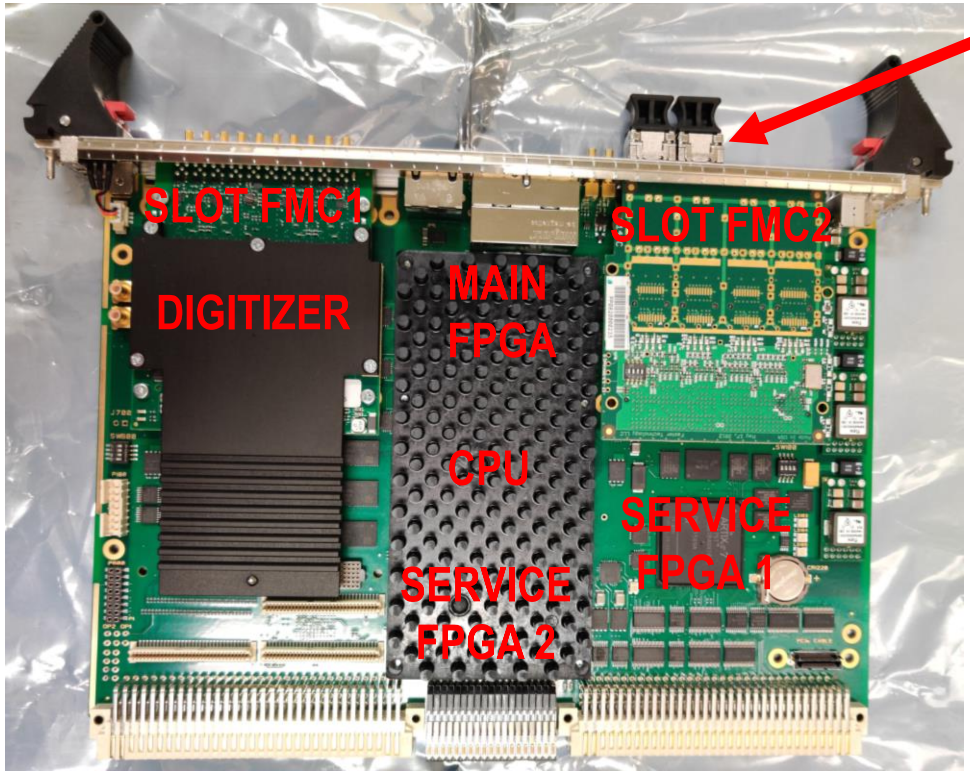
NO NEED TO REPLACE THE DETECTOR

FOCUS OF THE UPGRADE!

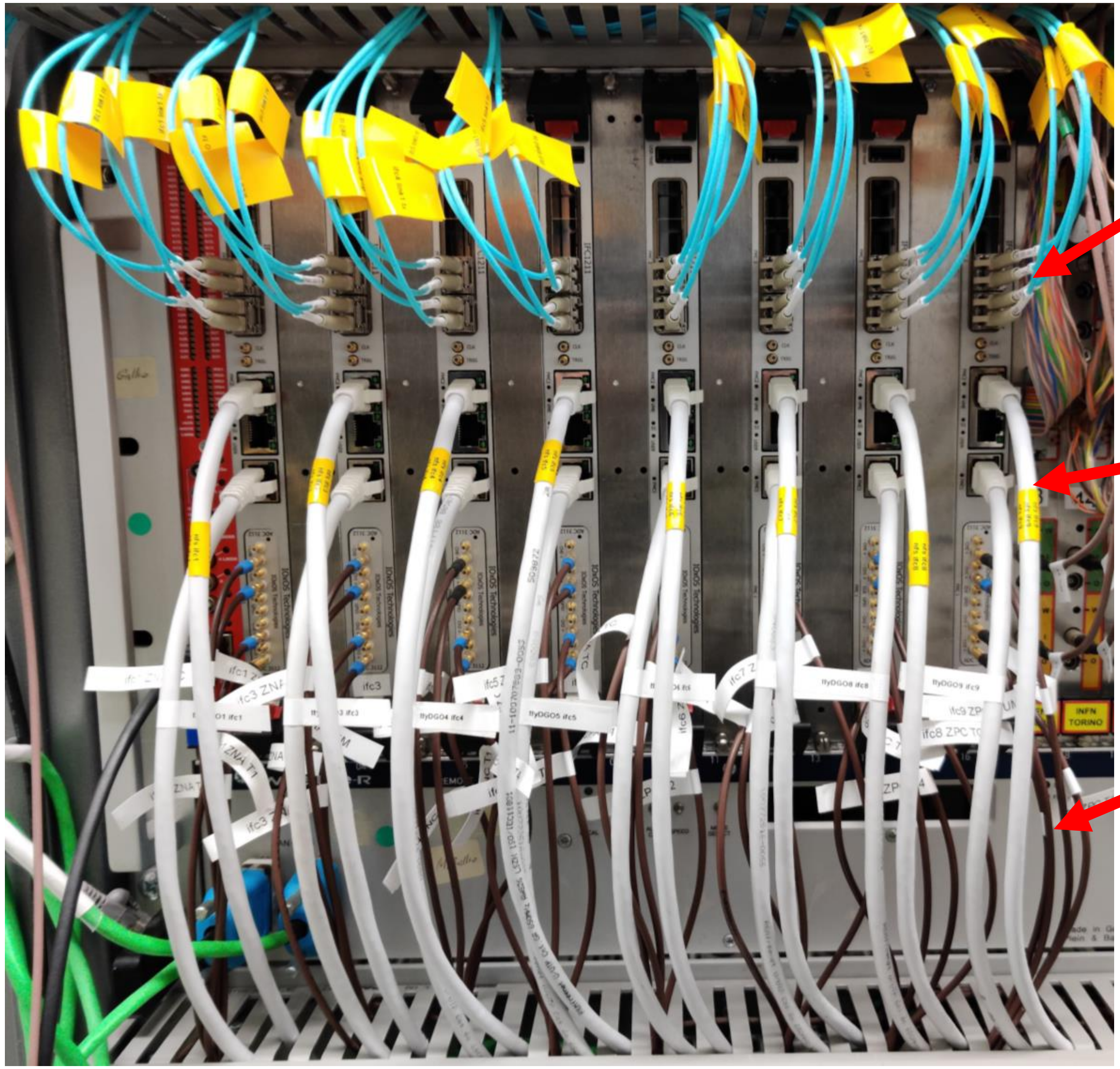
The fast digitizer selected for the upgrade:

- IOXOS FMC digitizer ADC 3112, mounting a TI ADS5409 digitizer. Maximum sampling rate of 1 Gsps, 1 Vpp dynamics, 12-bit resolution with ENOB of 10-bit, 4 channels per module, DC coupling (important for unipolar photomultiplier signals), working with digital filtering and decimation by 2.
- The triggering is performed on digitized data.

FPGA carrier:



TAS-A2NH1-P11, multimode, 850 nm, SFP+ optical transceivers.



Optical Fiber TX/RX

File system

Analog signal IN

- IOxOS ifc1211 carrier equipped with two FMC ports, a Xilinx FPGA Kintex Ultrascale xcku040-1ffva1156 and a PowerPC processor.
- 8 carriers are currently deployed in ALICE CR4. There are a total of 32 usable channels.

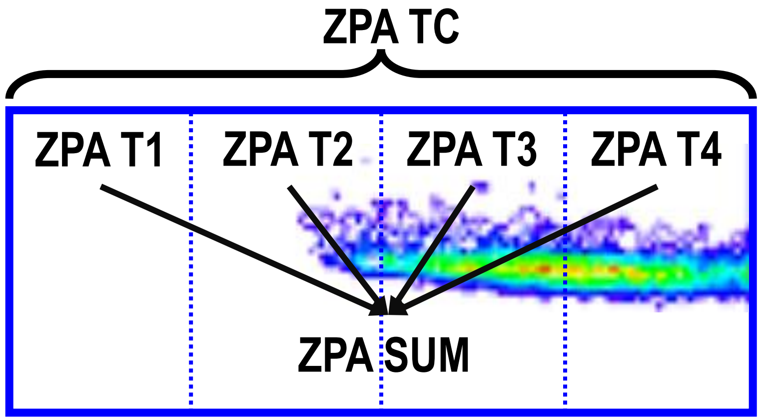
Readout strategy and cabling:

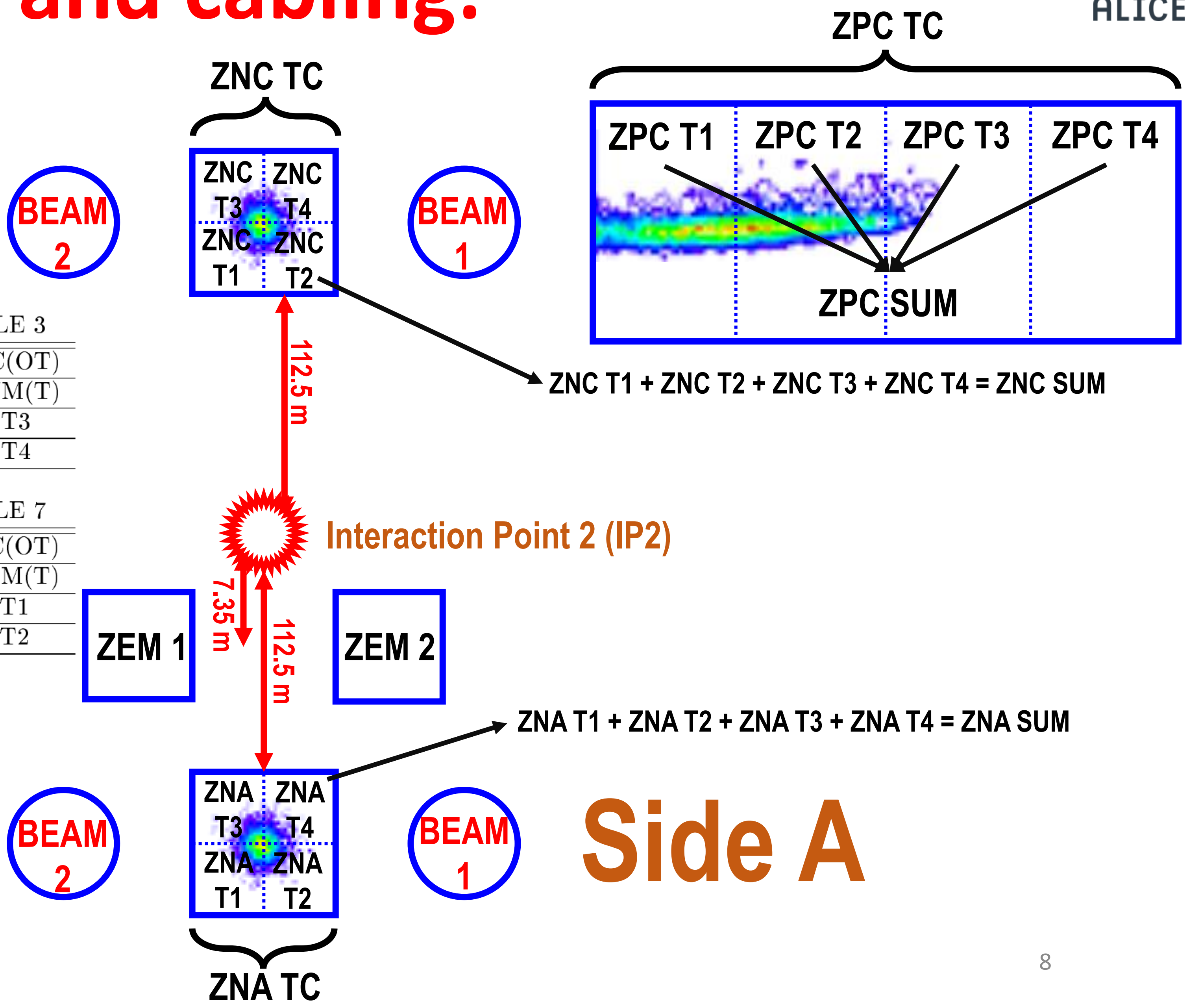
Cabling of each IFC1211 module of the upgraded ZDC readout system.
T = Trigger. OT = Only Trigger. S = Spare.

Side C

	MODULE 0	MODULE 1	MODULE 2	MODULE 3
ch 0	ZNA_TC(T)	ZNA_TC (OT)	ZNC_TC(T)	ZNC_TC(OT)
ch 1	ZNA_SUM(OT)	ZNA_SUM(T)	ZNC_SUM(OT)	ZNC_SUM(T)
ch 2	ZNA_T1	ZNA_T3	ZNC_T1	ZNC_T3
ch 3	ZNA_T2	ZNA_T4	ZNC_T2	ZNC_T4

	MODULE 4	MODULE 5	MODULE 6	MODULE 7
ch 0	ZPA_TC(T)	ZPA_TC (OT)	ZPC_TC(T)	ZPC_TC(OT)
ch 1	ZEM1(T)	ZPA_SUM(T)	ZEM2(T)	ZPC_SUM(T)
ch 2	ZPA_T1	ZPA_T3	ZPC_T3	ZPC_T1
ch 3	ZPA_T2	ZPA_T4	ZPC_T4	ZPC_T2





Firmware structure and features:

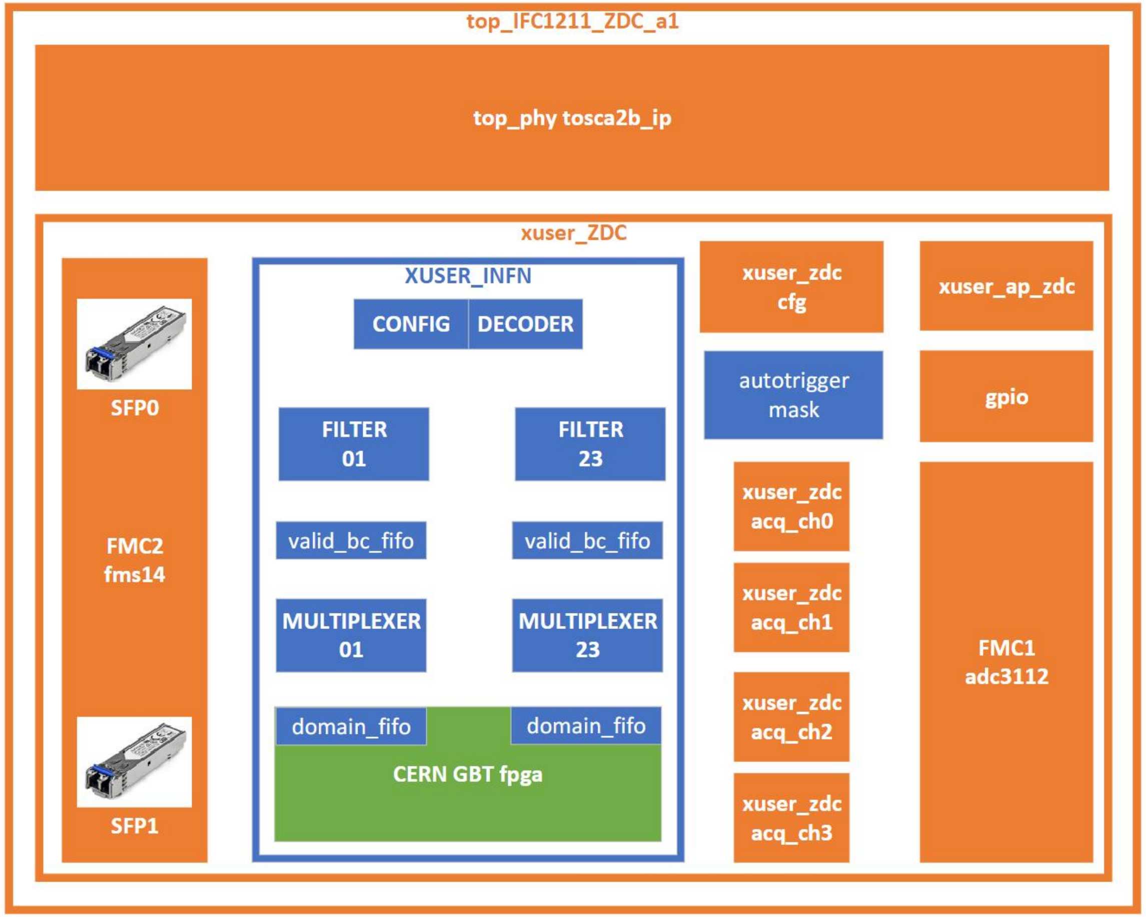
The part of the firmware that interfaces with the hardware was developed by a Swiss company, IOXOS, under detailed INFN specifications. For the fiber optic communication, a CERN IP was used, the GigaBit Transceiver (GBT) 4.8 Gbps. The rest of the logic, i.e. data processing and formatting, was developed by INFN.

Key features:

- Auto trigger algorithm.
- Automatic baseline evaluation.
- Rate measurement capabilities.
- Auto calibration system.

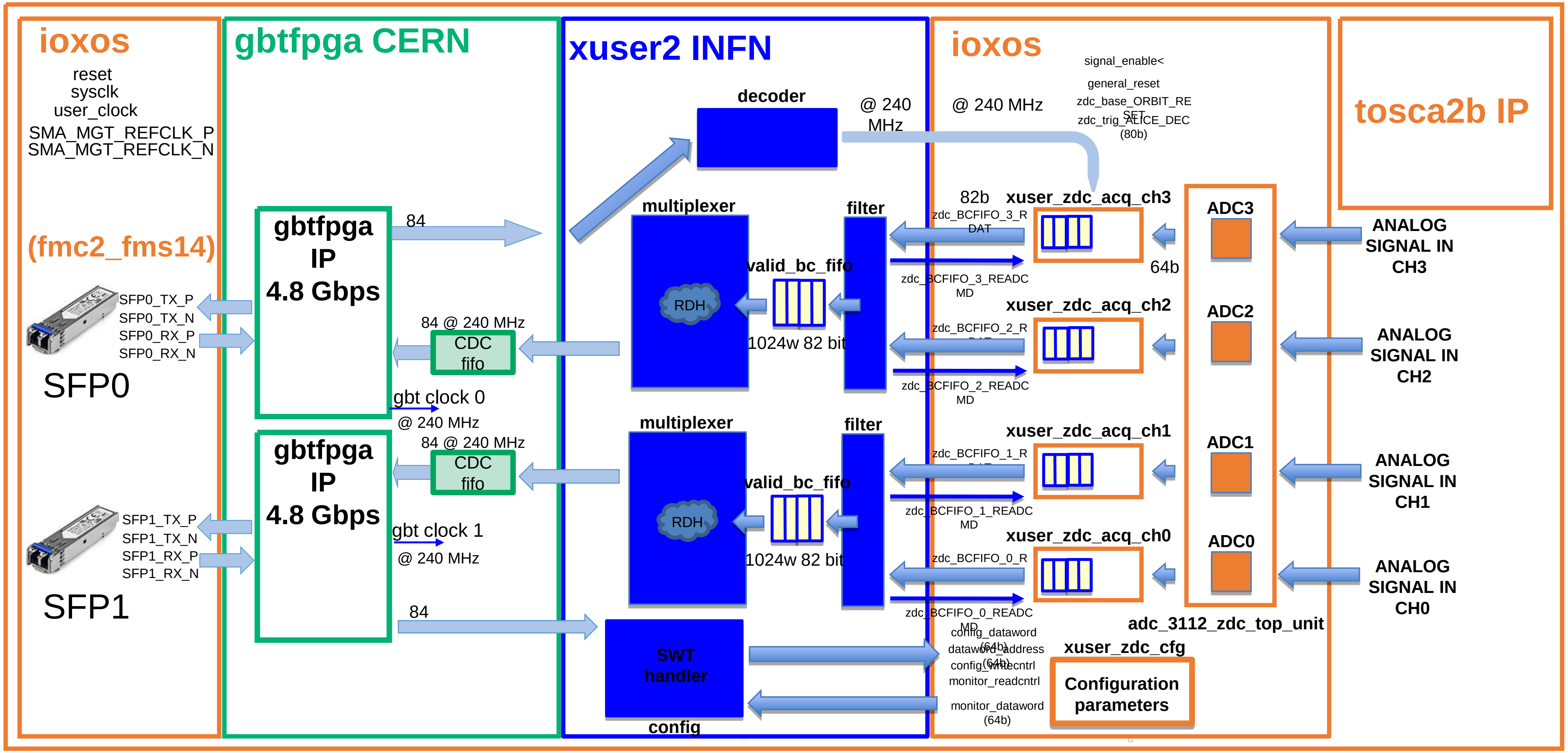
- Auto reset logic (optical link status monitoring).
- Fiber controlled slow control.
- Backpressure detection and protection.
- Configuration of channel role (triggering/readout).

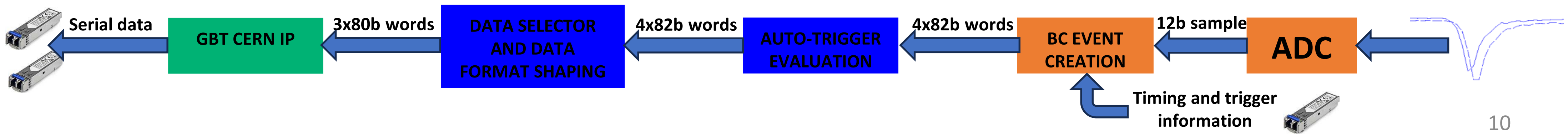
INFN CERN IOXOS



Firmware development using XILINX VIVADO 2018.3 software.

Firmware block diagram:





Auto trigger algorithm:

Due to the high rate and pile-up presence, a trigger related to a simple threshold does not fit with the requirement to select events that have such large dynamics, from 1 neutron to ~60.

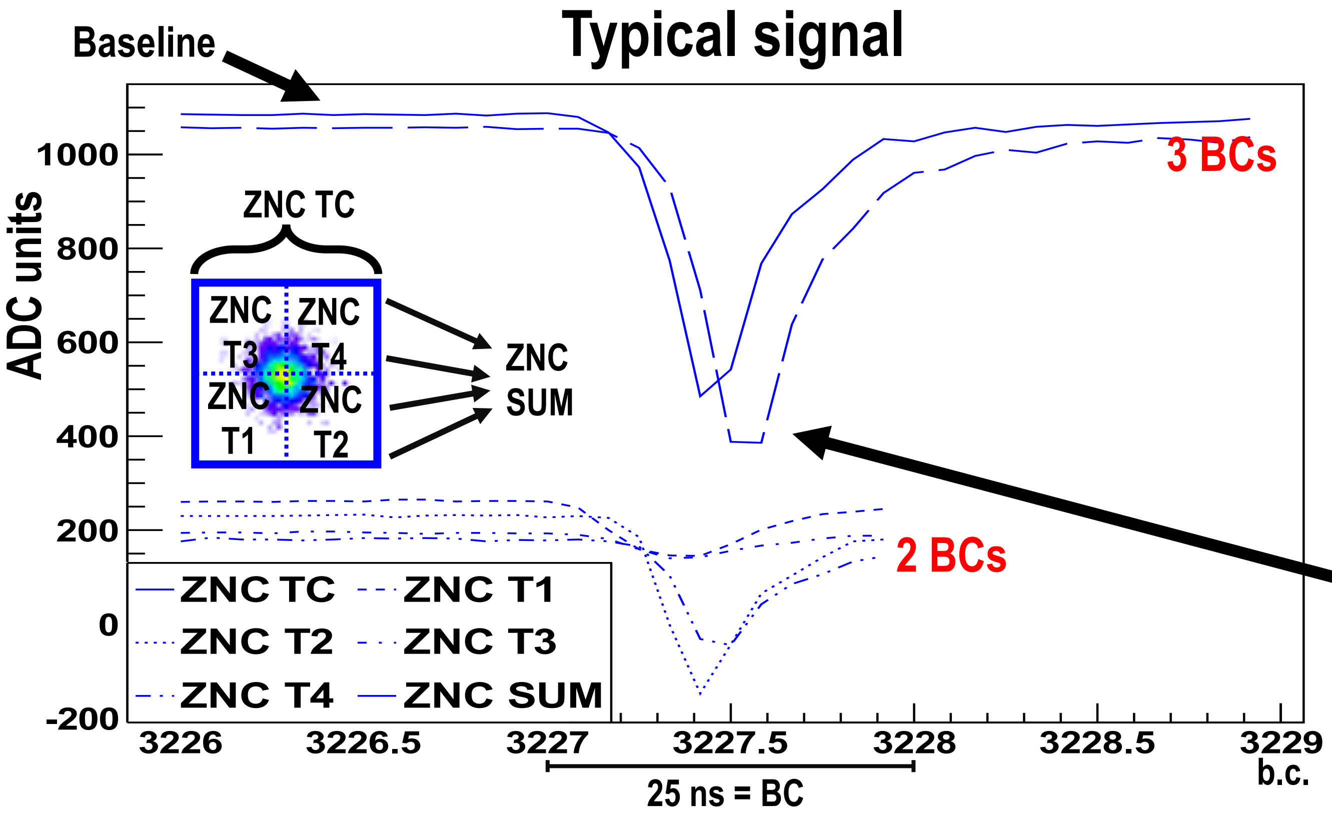
An algorithm evaluating the differences between samples has been developed by INFN Torino. This behaves like a differential threshold, thus a threshold (*t*) on the derivative of the signal.
Indicating with y_i the i^{th} ADC sample and considering that the signal has negative polarity.

$T = (y_i - y_{i+k} > t) \wedge (y_{i+1} - y_{i+k+1} > t)$ ← **Double condition.**

$T = (y_i - y_{i+k} > t) \wedge (y_{i+1} - y_{i+k+1} > t) \wedge (y_{i+2} - y_{i+k+2} > t)$ ← **Triple condition.**

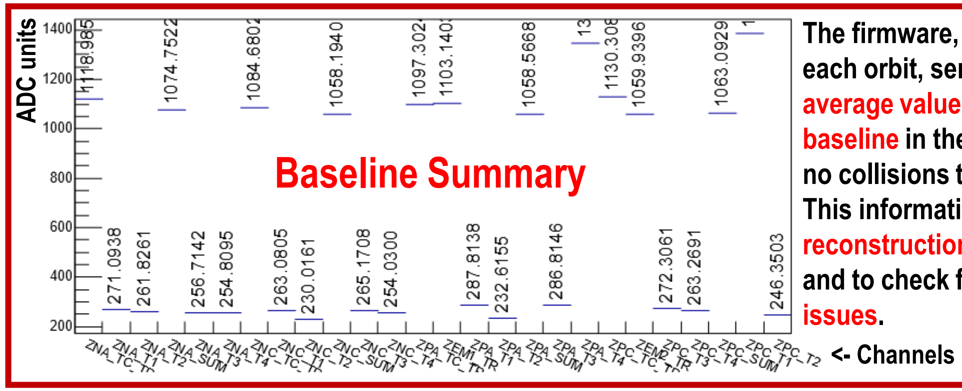
The Firmware allows to select between the **Double** and **Triple** condition, to configure the threshold value t, and the sample separation *k*.
Typical operational values for PbPb data taking are *t*=10, *k*=4 with Double condition.

Main firmware features:



The logic can be configured to send **3 BCs** (36 samples) for triggering channels, **2 BCs** (24 samples) for standard channels or **10 BCs** (120 samples) for special data taking conditions.

The auto calibration system, that is performed automatically at each LHC fill, places the interesting part of the waveform at the **center of the BC** by means of a **configurable delay parameter**. This operation is channel indipendent



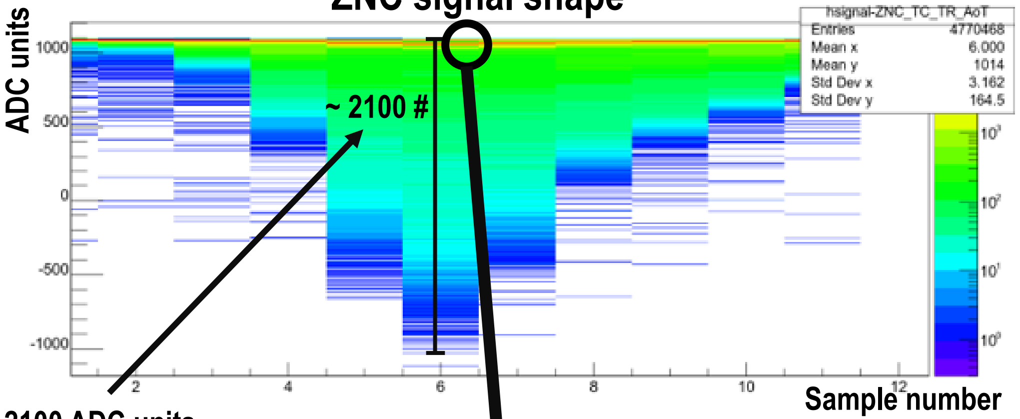
The firmware, at the end of each orbit, sends the **average value of the baseline** in the BCs where no collisions take place. This information is used for **reconstruction purposes** and to check for **cabling issues**.

Each readout channel is **completely indipendent** and can have different **readout and auto-trigger configuration** to respect to its neighbors.

Performance in 2022 pilot Pb-Pb 2.68 A TeV:

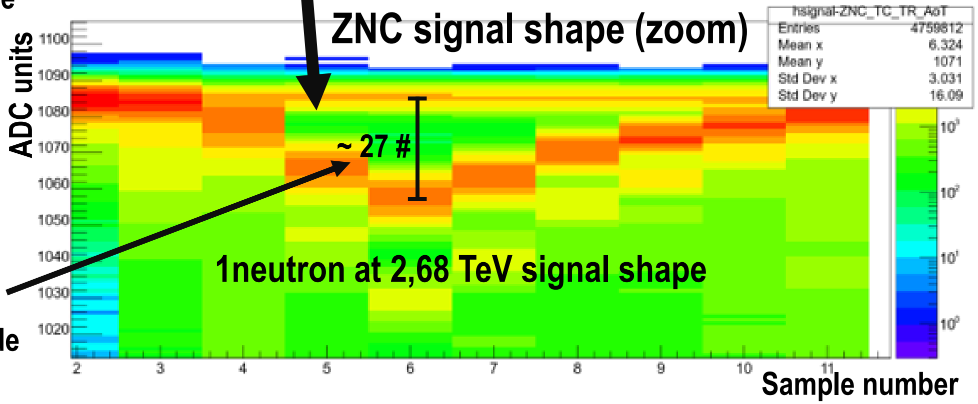
Large signal dynamics!

ZNC signal shape



2100 ADC units means ~ 620 mv signal amplitude

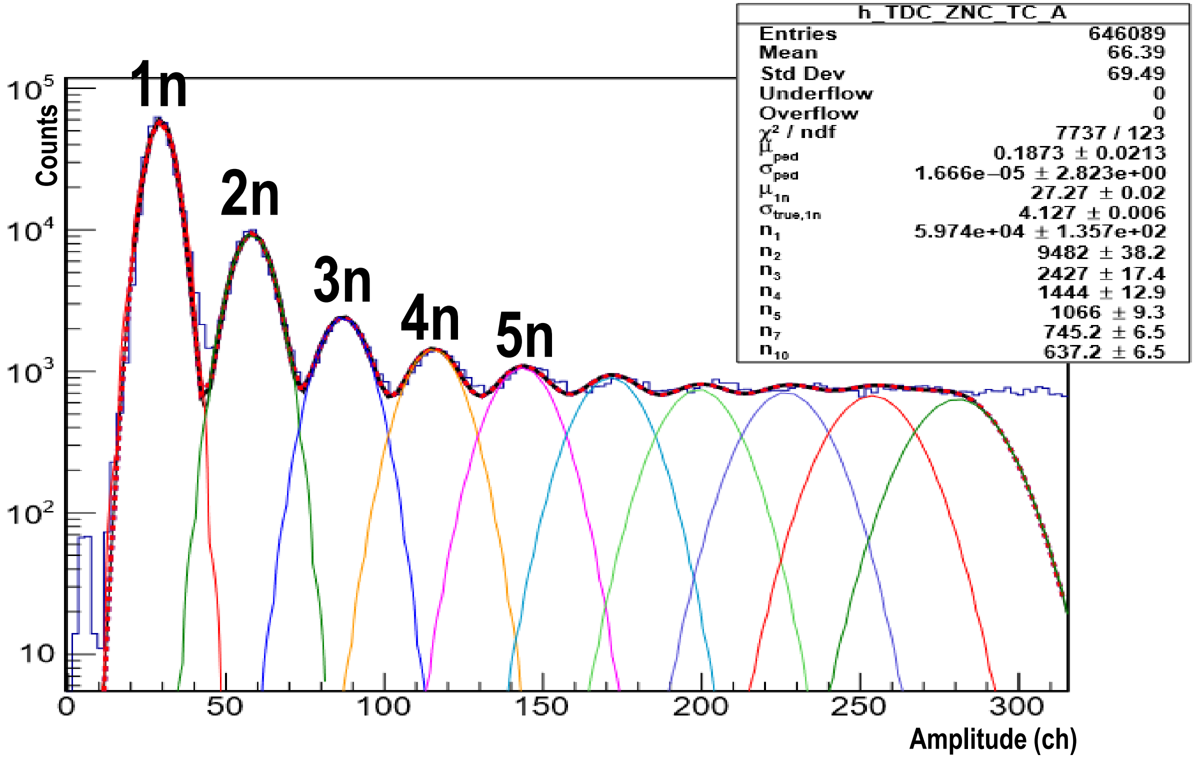
ZNC signal shape (zoom)



27 ADC units means ~ 8 mv signal amplitude

12 samples = 1 B.C. = 25 ns → 1 sample ~ 2.08 ns

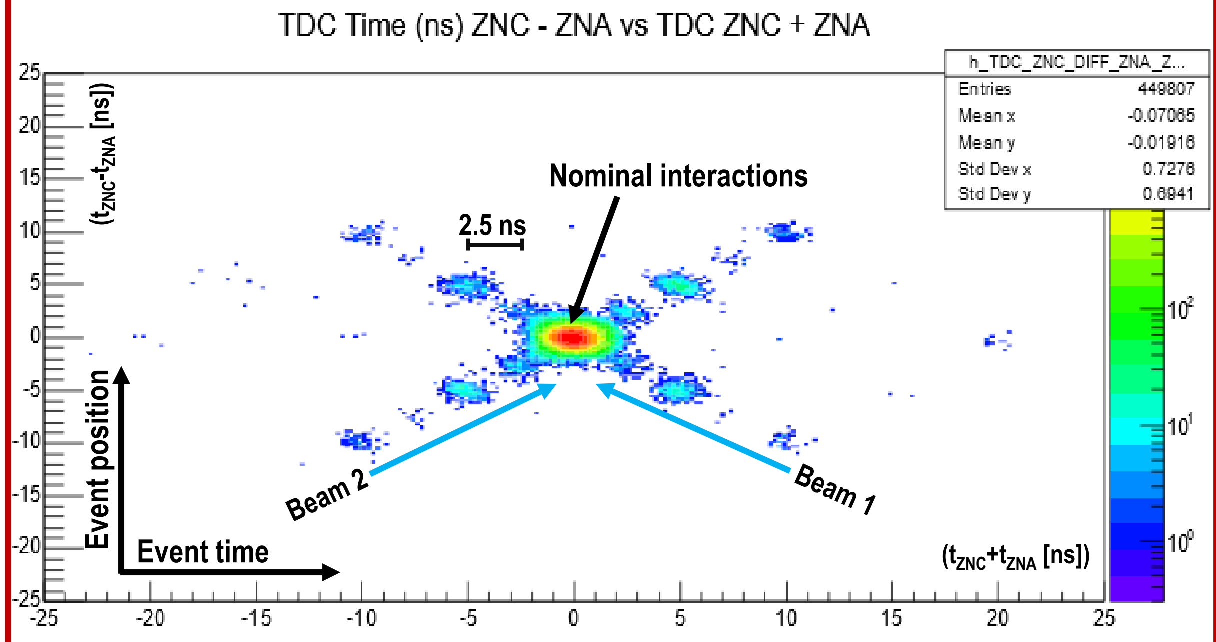
Energy resolution:



1n peak resolution ~ 15%-16%.
It was 20% in run1 and run2.

Performance in 2022 pilot Pb-Pb 2.68 A TeV:

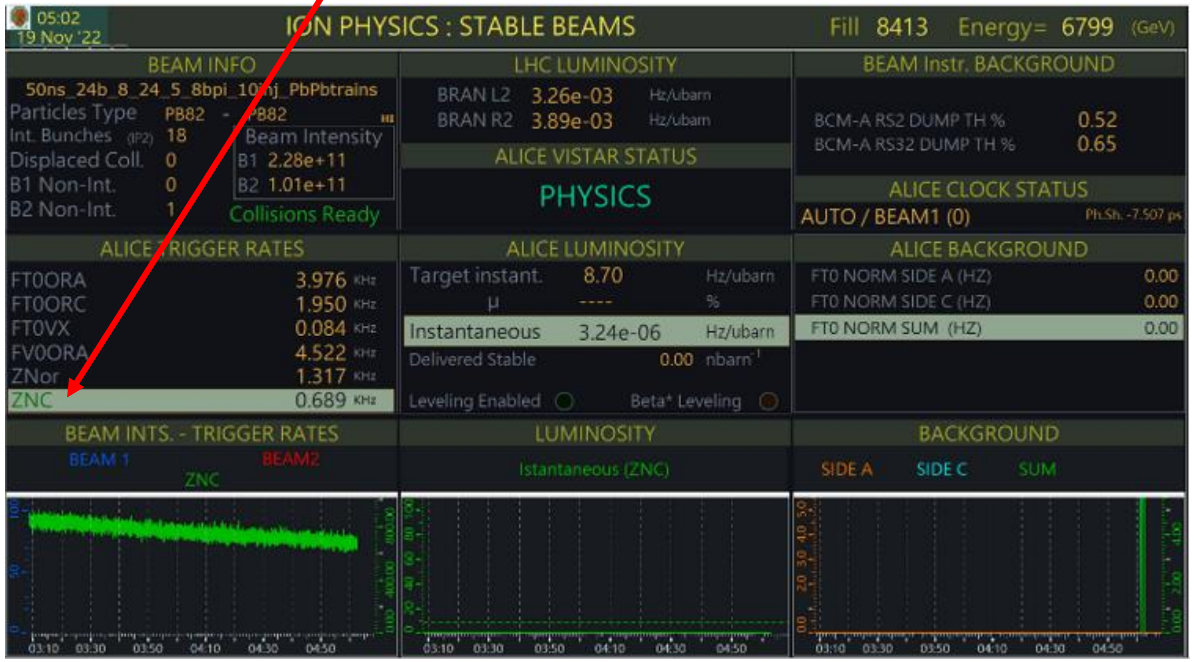
Time resolution and rejection of satellites:



LHC RF cavities frequency = 400 MHz.

Luminosity estimation:

During the low rate pilot Pb Pb run of November 2022 ZNC operated as the ALICE luminometer, measuring the rate of neutron emission in e.m. dissociation + hadronic interactions.



Summary and outlook:

A new FPGA based readout system for the ALICE ZDC detector has been developed for Run 3 which is able to operate in self–triggered mode without dead time at a rate of 2.5 Mevent/s.

The commercial 12 bit 1 GSps digitizers from IOXOS allow an energy resolution of 15 % for the amplitude for the single neutron peak, better than Run 2.

The new readout system is fully compliant with the different acquiring modes foreseen in ALICE and a first successful commissioning was done in November 2022 in proton-proton and Pb-Pb collisions at low luminosity.

The ZDC is expected to take data in October 2023 during the Pb-Pb period at the nominal rate of 50 KHz.

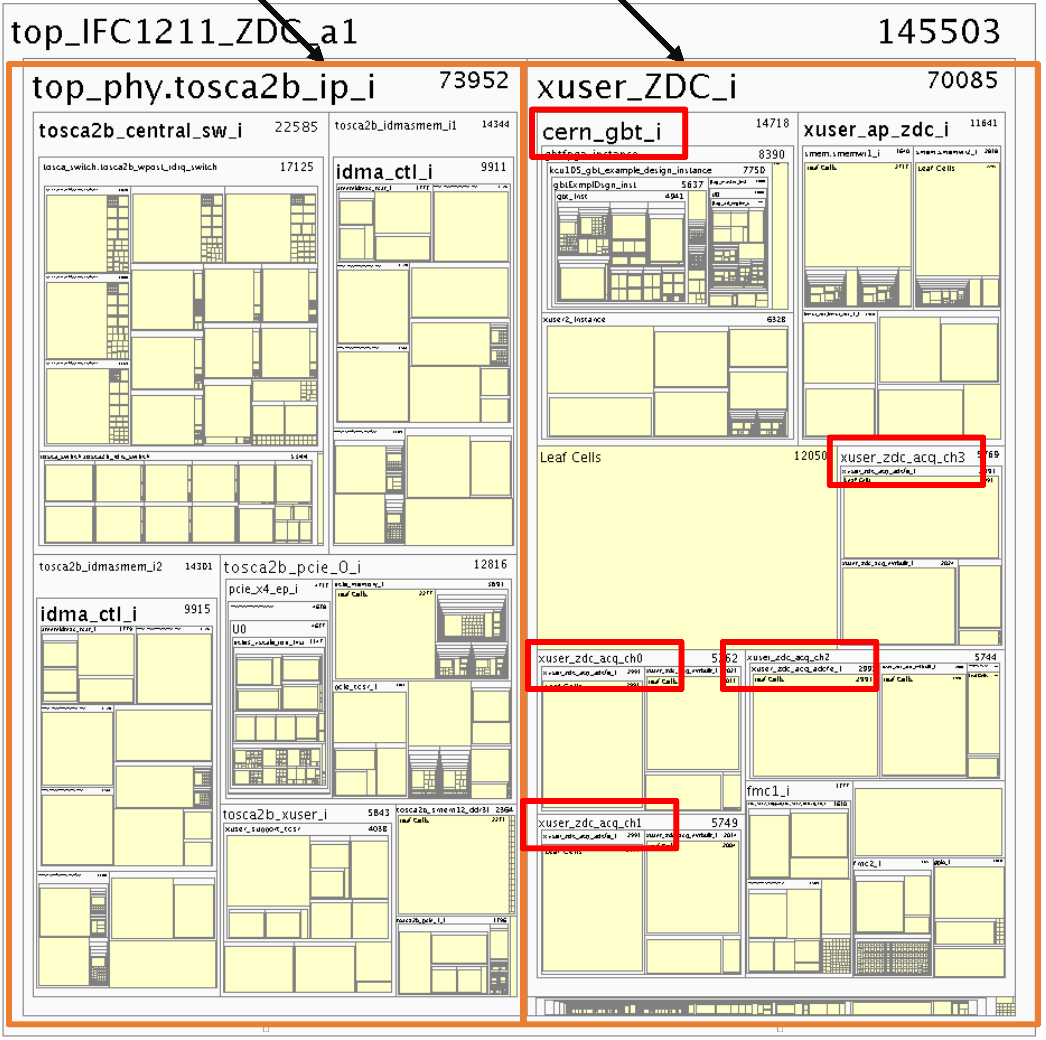
Thank you for your attention!

BACKUP

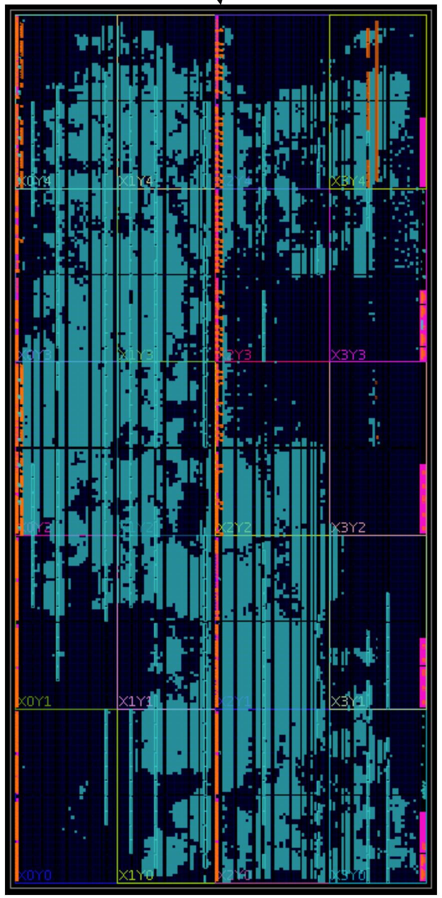
Firmware reports:

IOXOS TOSCA IP

ZDC FW



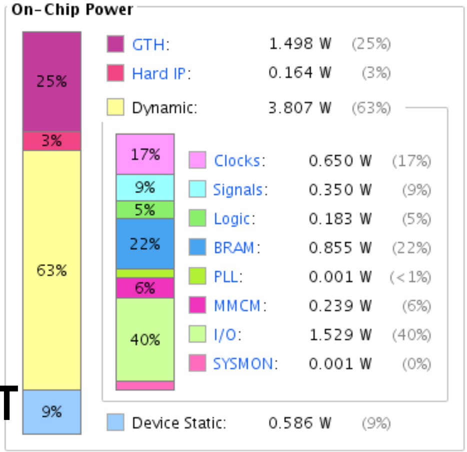
FPGA LAYOUT



Power analysis from Implemented netlist. Activity derived from constraints files, simulation files or vectorless analysis.

Total On-Chip Power:	**6.056 W**
Design Power Budget:	**Not Specified**
Power Budget Margin:	**N/A**
Junction Temperature:	**33.6°C**
Thermal Margin:	51.4°C (35.4 W)
Effective ϑJA:	1.4°C/W
Power supplied to off-chip devices:	0 W
Confidence level:	Low

Launch Power Constraint Advisor to find and fix invalid switching activity



FPGA POWER REPORT

FPGA POST-IMPLEMENTATION UTILIZATION REPORT

Utilization Post-Synthesis | **Post-Implementation**

Graph | **Table**

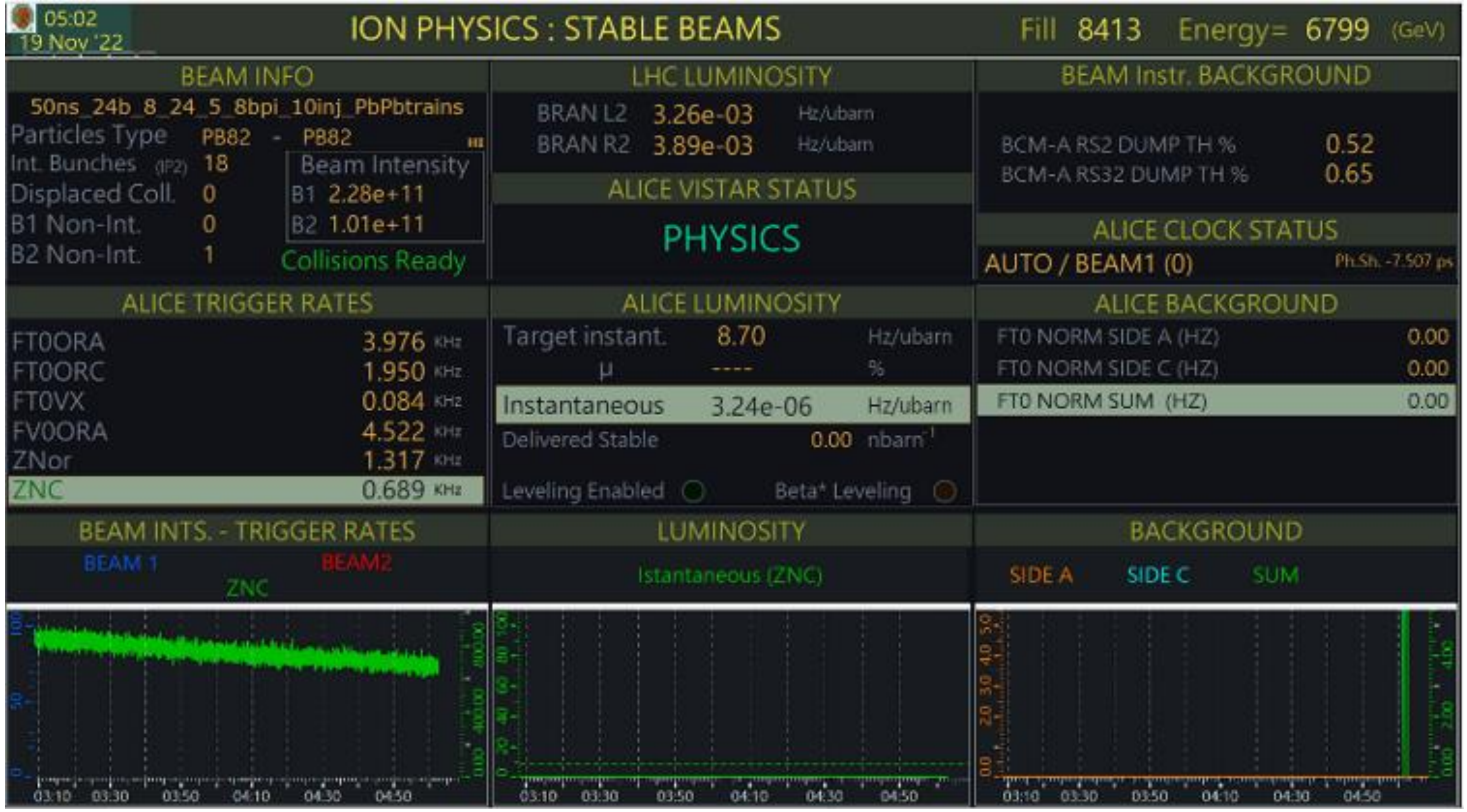
Resource	Utilization	Available	Utilization %
LUT	63643	242400	26.26
LUTRAM	909	112800	0.81
FF	66511	484800	13.72
BRAM	329	600	54.83
IO	444	520	85.38
GT	6	20	30.00
BUFG	36	480	7.50
MMCM	6	10	60.00
PLL	1	20	5.00
PCIe	1	3	33.33

FPGA TIMING REPORT

Setup		Hold		Pulse Width	
Worst Negative Slack (WNS):	0.031 ns	Worst Hold Slack (WHS):	0.024 ns	Worst Pulse Width Slack (WPWS):	-0.011 ns
Total Negative Slack (TNS):	0.000 ns	Total Hold Slack (THS):	0.000 ns	Total Pulse Width Negative Slack (TPWS):	-0.030 ns
Number of Failing Endpoints:	0	Number of Failing Endpoints:	0	Number of Failing Endpoints:	6
Total Number of Endpoints:	146078	Total Number of Endpoints:	145306	Total Number of Endpoints:	69124

Auto-trigger rate for luminosity estimation:

During the low rate pilot Pb Pb run of November 2022 ZNC operated as the ALICE luminometer, measuring the rate of neutron emission in e.m. dissociation + hadronic interactions.



Rate of ZNC is given by EMD plus hadronic interactions.

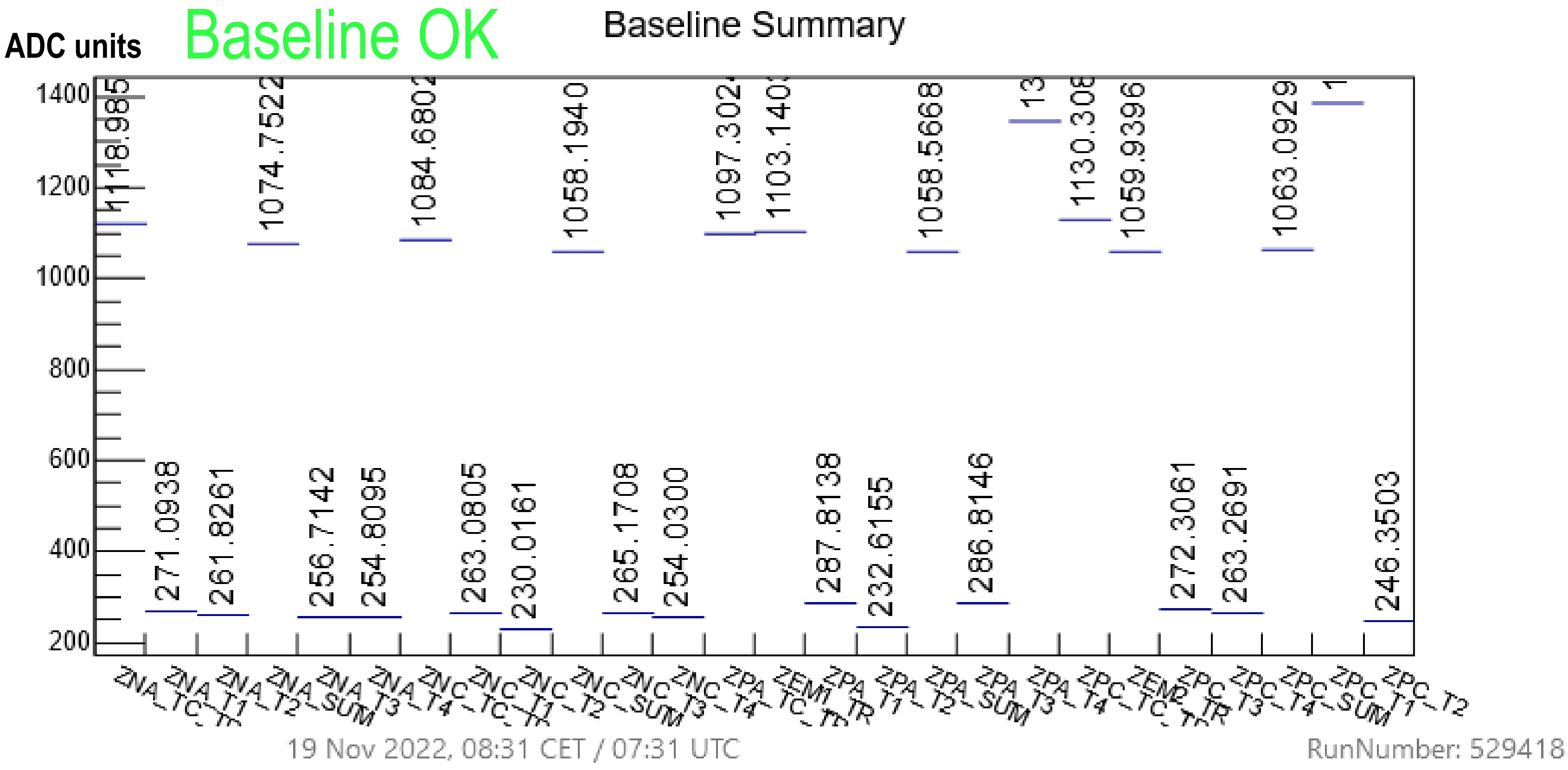
Absolute luminosity:

$L \sim Rate_{ZNC}/(206,8 + 7,67)$ b

Igor Pshenichnov, UPC meeting | 1 November 2022

ZN detection probability for neutrons emitted in EMD of Pb nuclei and hadronic interactions -> ~99%.

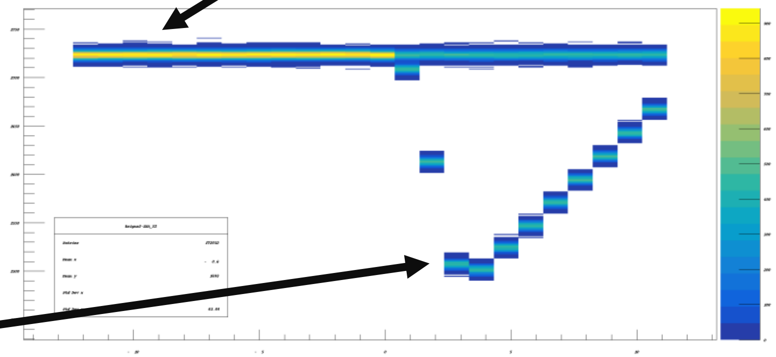
Baseline estimation as input for reconstruction:



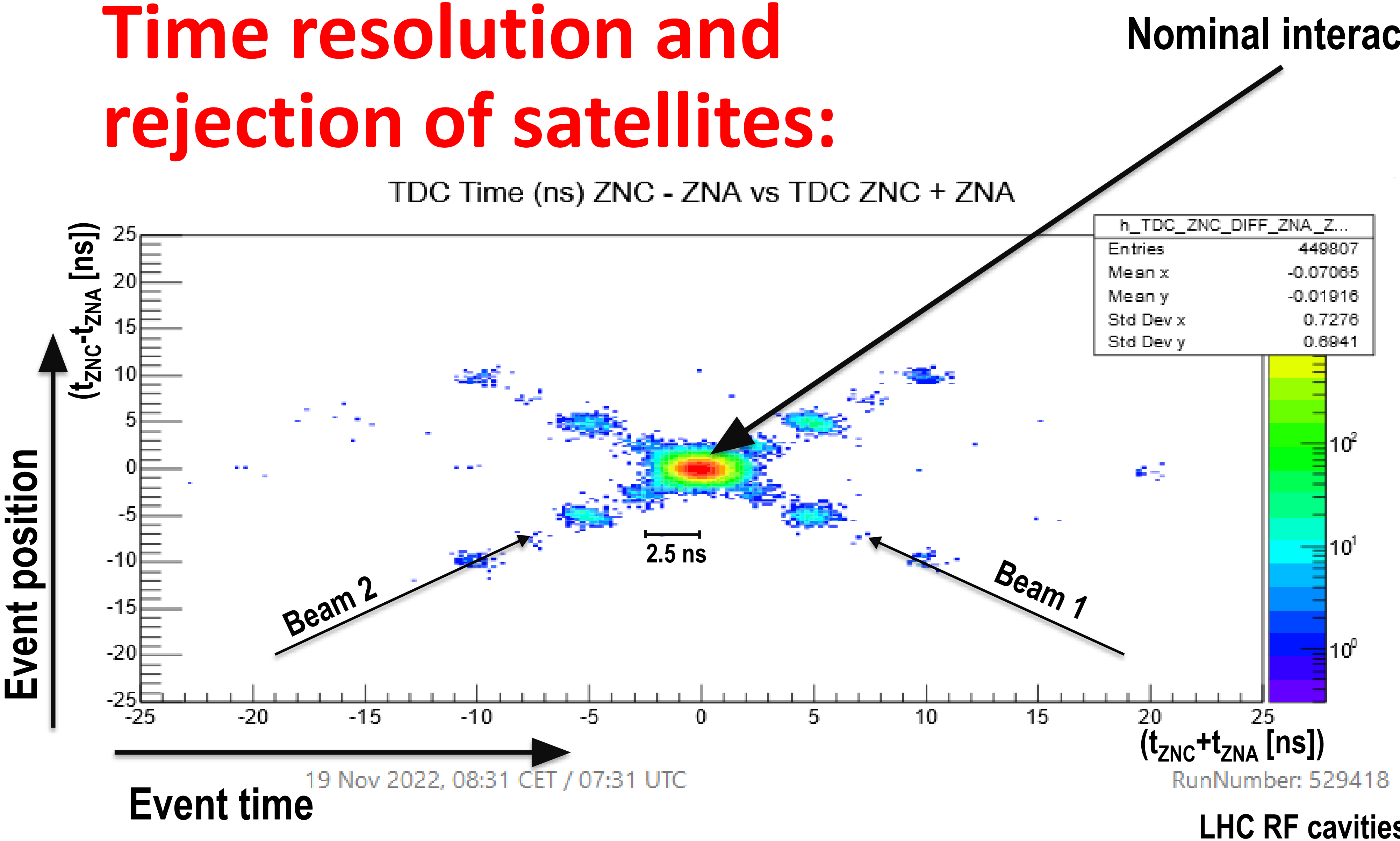
Baseline information received from firmware for each channel.

Used for:

- Event reconstruction.
- Check for cabling issues.



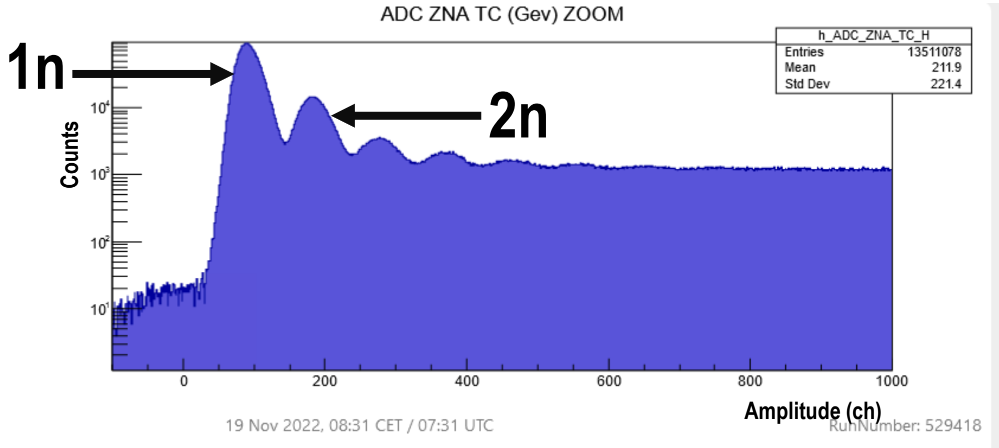
Time resolution and rejection of satellites:

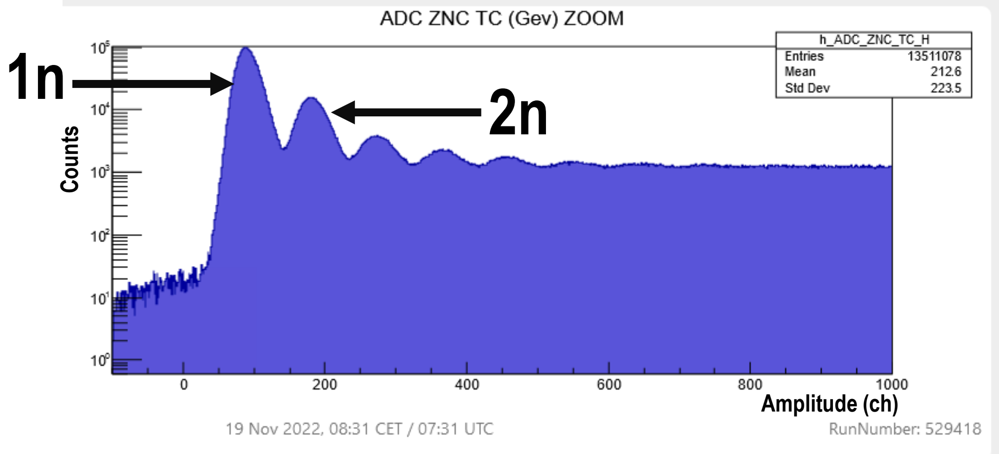


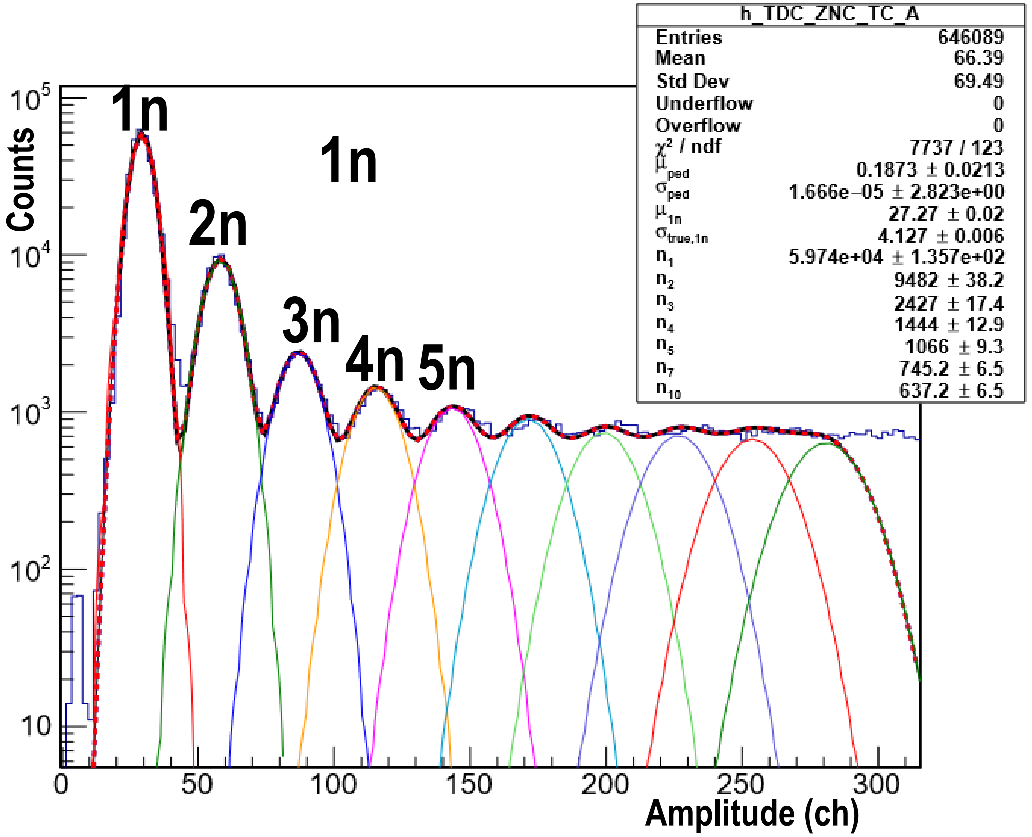
The large cluster in the middle corresponds to collisions between ions in the **nominal RF buckets** of each beam, while the small clusters along the diagonal (spaced by **2.5 ns** in the time difference) correspond to collisions in which one of the ions is displaced by **one or more RF buckets**.

LHC RF cavities frequency = 400 MHz.

Amplitude spectra & energy resolution:







- ADC spectrum for ZNA TC, ZNC TC.
- The 1n, 2n, 3n and 4n peaks are clearly visible.

- A fit shows that the resolution is increased respect to the previous readout system.
- 1n peak resolution ~ 15%-16% -> was 20% in run1 and run2.