ATLAS ITk BCM'

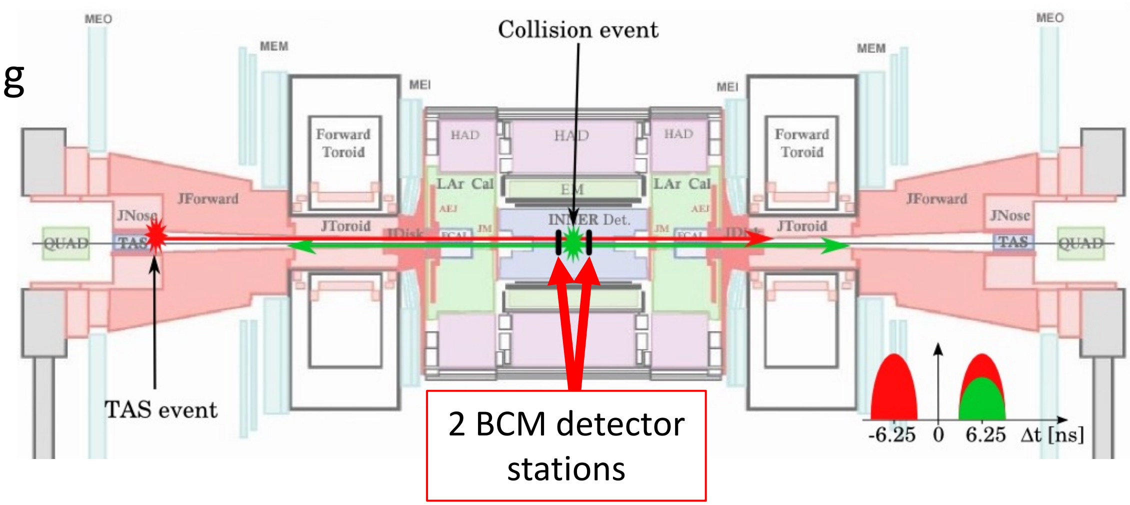
VERTEX 16-20 October 2023

Ignacio Asensi, CERN

on behalf of all BCM' Community

BCM' – Beam and Lumi protection

- BCM – Beam Conditions Monitoring
- Provides bunch-by-bunch for asynchronous detection
  - Fast safety system for ATLAS (>105 MIP)
  - Luminosity measurement (MIP)
  - Background monitoring (MIP)



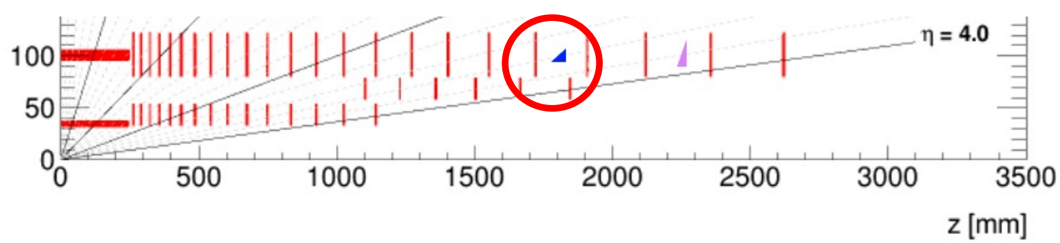
BCM' TOF concept

- **Collisions: in-time**
- **Background: out-of-time**

- Part of the new ATLAS ITk, BCM’ is the upgrade similar in operating principle to BCM
- Two detector rings mounted symmetrically at z~1875 mm (6.25 ns)
  - Four detector stations on each ring
- Background events selected based on Time-of-Flight measurement
- phi = 0°, 90°, 180°, 270° for lumi

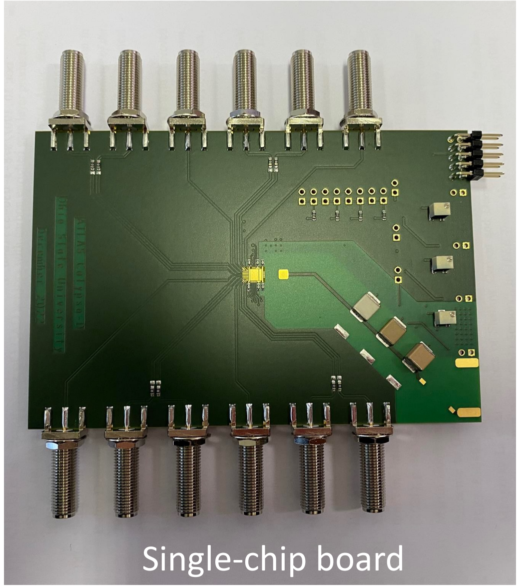
Out-of-time events indicate possible beam instabilities. Abort conditions are met if 3 out of 4 detector stations on each ring trigger in two consecutive beam orbits

BCM' R1 ring position

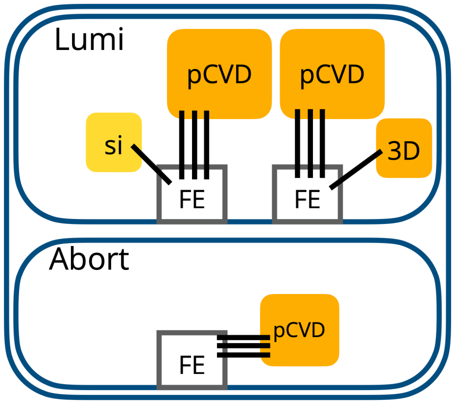


BCM' – Front-end Calypso

- pCVD* diamonds selected for main detector material
- Insulator at room temperature, no cooling required
  - High electric field of up to 2V/ µm produces fast signals
- Suitable for high radiation environments
- Four channels, each FE amplifier and CFD configurable separately
- Abort (8.2μ V/fC FE gain) or Lumi (60m V/fC FE gain) functionality
- 1 ns rise-time, 100 ps jitter, 200 e- noise for 2 pF detector capacitance
- Outputs LVDS signal with ToA and ToT information foreach channel
- Full feature design: 256 step of CFD threshold range, internal pulser, I2C addressing, and bandgap voltage reference

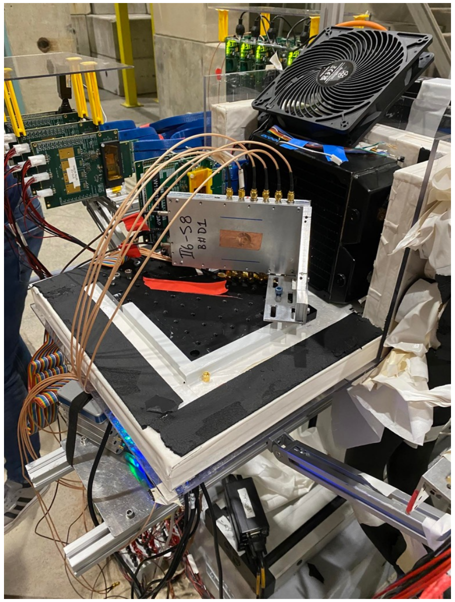


Single-chip board



- 2 **planar pCVD diamond** detectors
- 1 **3D pCVD diamond** detector
- 1 **silicon** detector for luminosity measurements per station

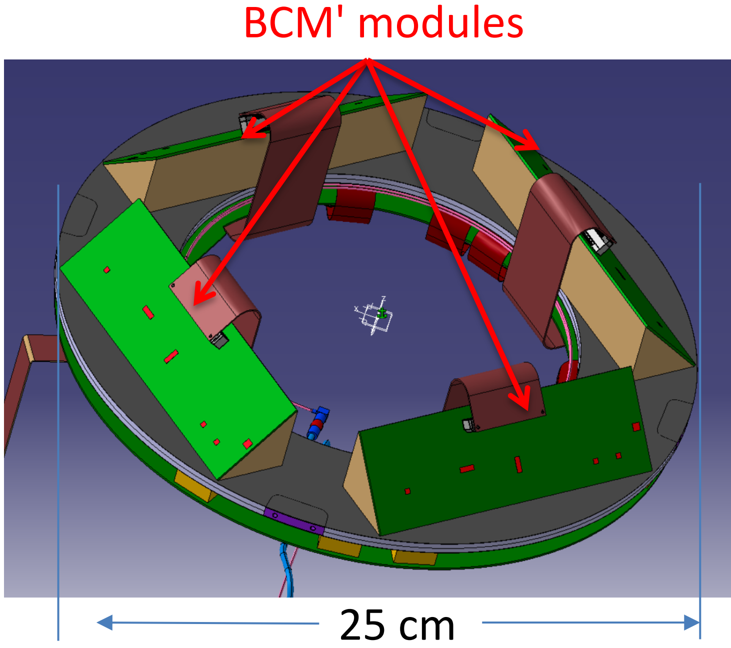
- 1 **planar pCVD diamond** detector for abort functionality

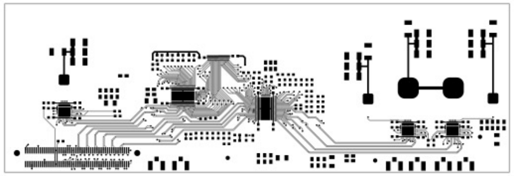


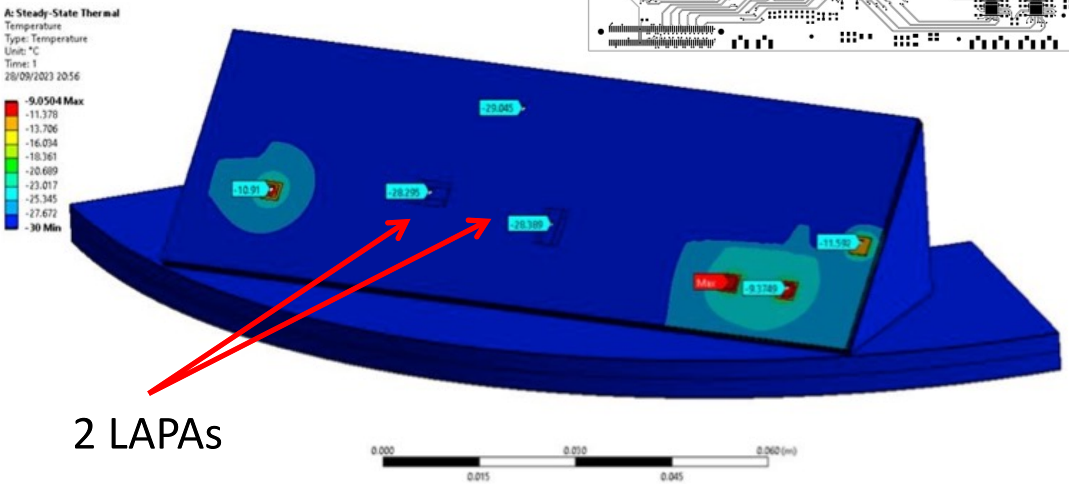
TB telescope and DUT

* polycrystalline Chemical Vapor Deposition

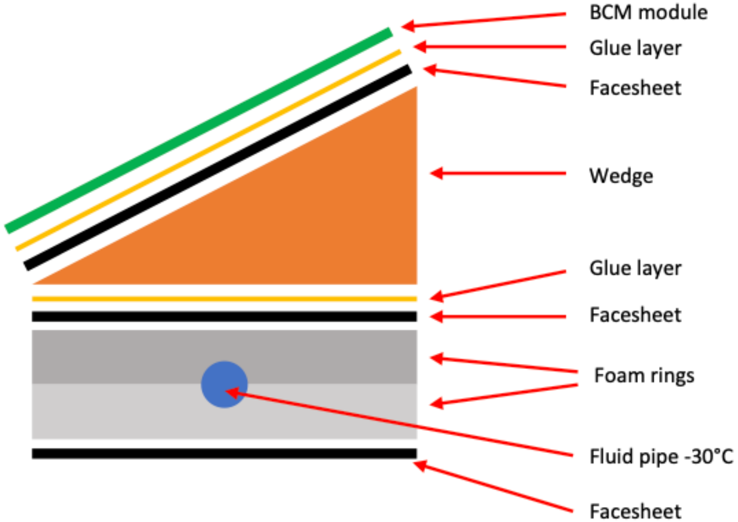
- Mounting of pCVD's at 45° angle difficult
  - Avoid degrading Calypso performance
- Opted for large (120x40 mm) 4-layer board, square design, sensors mounted flat on board
  - Boards produced and stuffed
- Engineering implications of the inclined flat module
  - Envelopes check with Pixel IS
  - Thermal simulation
  - Carbon foam wedges







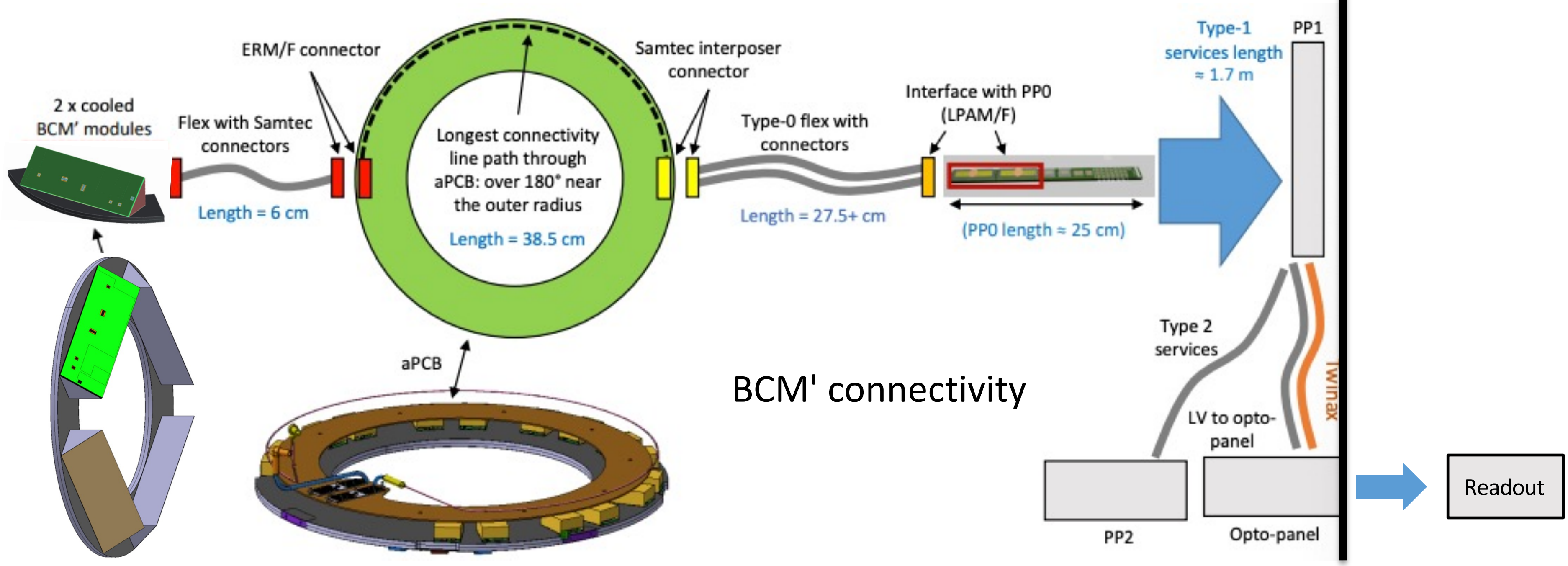
Temperature distribution obtained after simulation



Cut view of the model (normal to module's length)

BCM' – Services

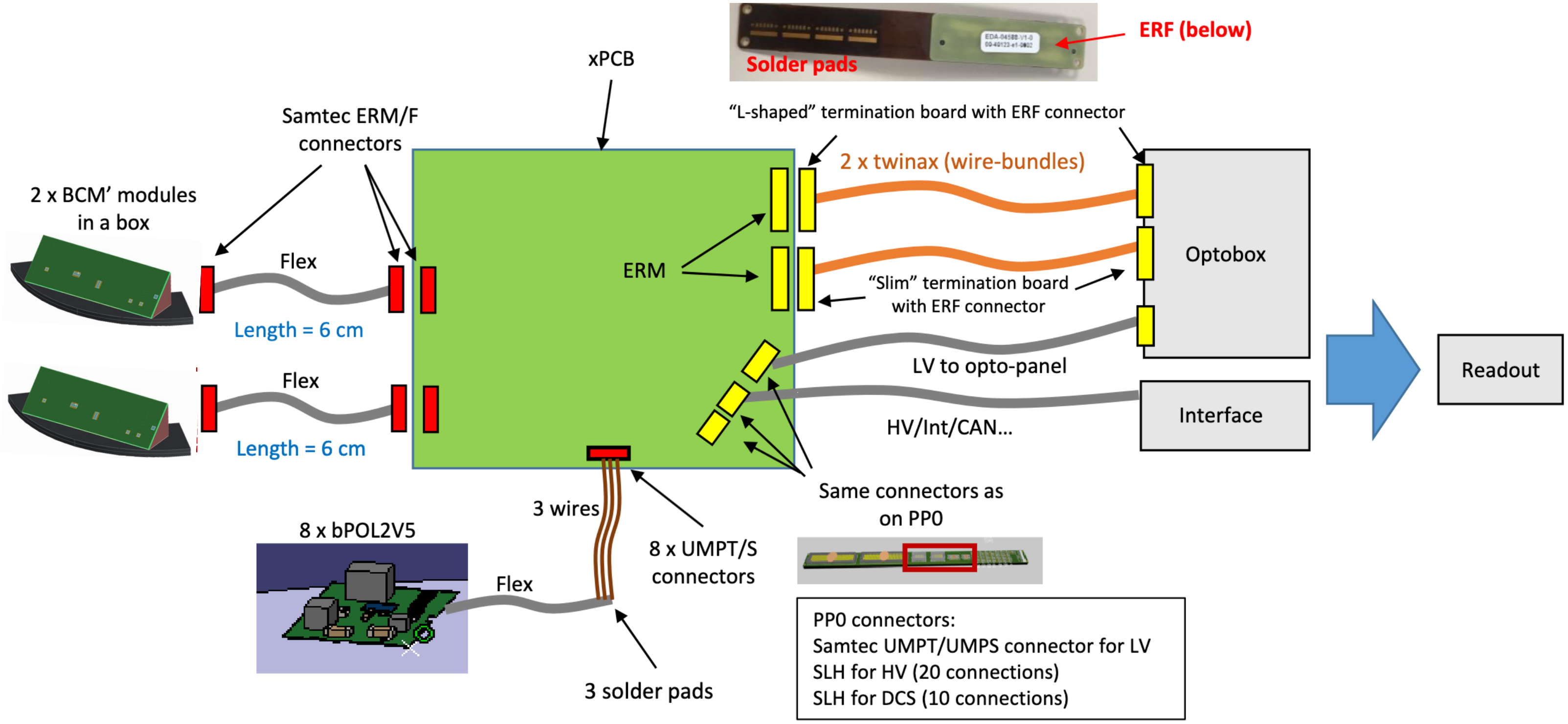
- BCM services baseline follows ITK Pixel Inner System with some differences
- aPCB being designed
- Data transmission: 12 ribbons with 2x(10+8+10) Twinax per side feeding 2 slim + 2 L-shaped opto-boards, 56 total (48 up-, 8 down-links)
- LV system uses DC-DC converters (bPOL), HV operates at 1000 V as opposed to 750 V in the Pixel IS
  - Two floating BCM' power sections with single bPOL12V
- Final G&S schematic reviewed



BCM' connectivity

BCM' – System tests

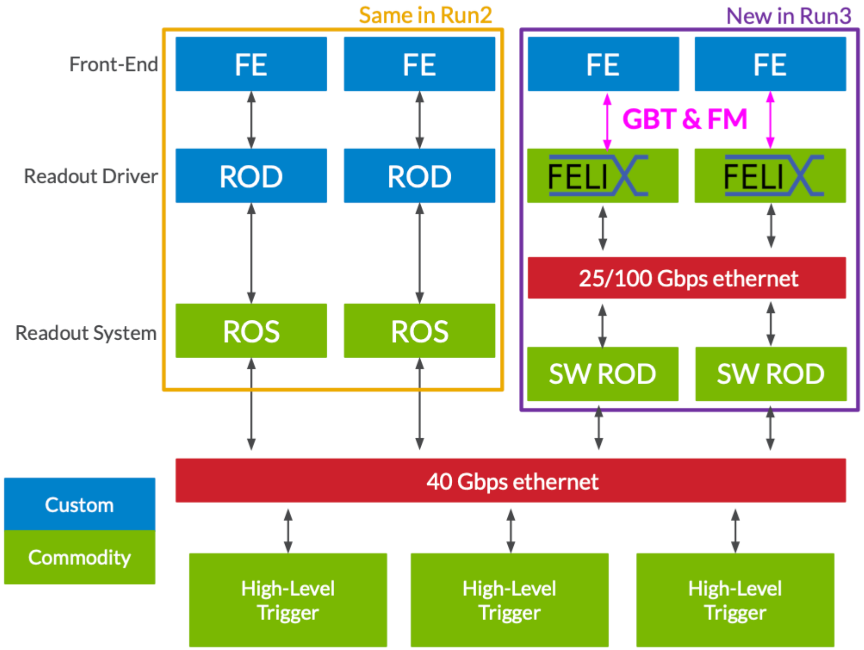
- Preparations for future tests ongoing
- Use many components from Pixel IS (OptoBox, bPOL2V5, Twinax, cables…)
  - Acquiring missing components (PP0, PP0_flex, PP1)
  - Still need to demonstrate system aspects (power, control, read-out) up to opto-box
- xPCB to incorporate aPCB + PP0 functionality – interface BCM' modules to opto-box

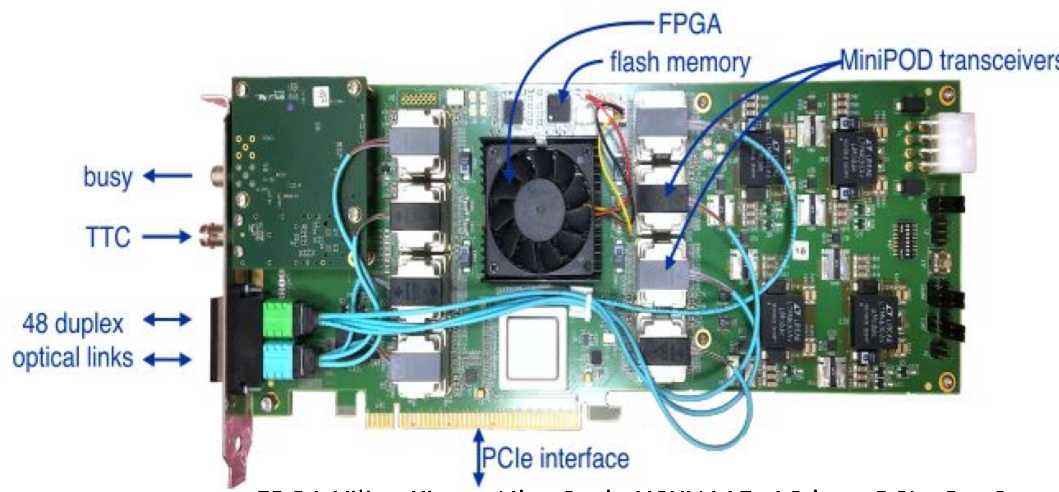


BCM’ – FELIX read-out

BCM’ read-out will be based on FELIX
Front-End LInk eXchange
https://atlas-project-felix.web.cern.ch

- Legacy ROD and ROS architecture is being replaced with FELIX and SW ROD
- Designed to reduce costs and custom electronics
- FELIX is a data router that works as an interface between on-detector systems and commodity computing
  - The data being routed includes readout, configuration, trigger, clock distribution, monitoring
  - FELIX system consists of commodity servers with PCIe cards. Used for data routing only
  - SWROD oversees data processing, aggregation, and monitoring. Hosted by commodity computers



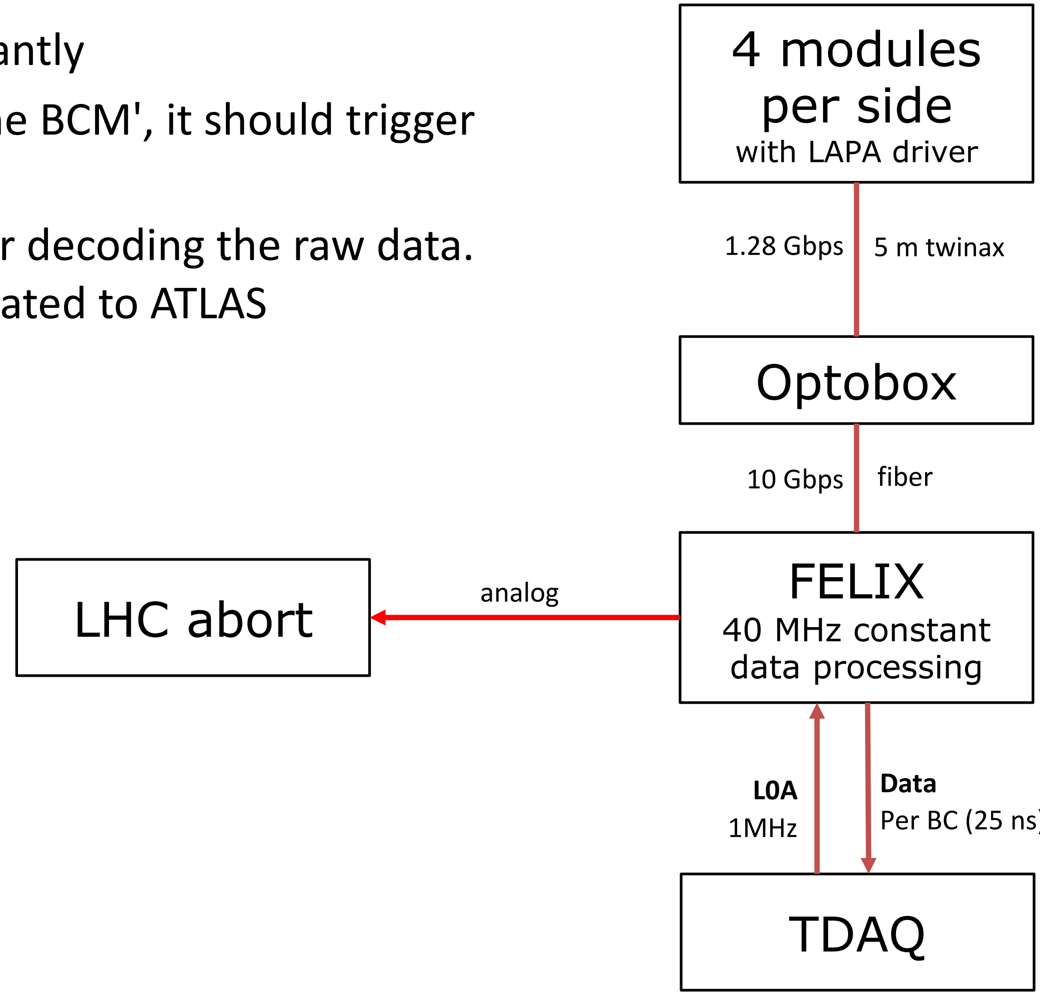


FPGA Xilinx Kintex UltraScale XCKU115, 16-lane PCIe Gen3

- 8 MiniPODs to support up to 48 bidirectional optical links (most commonly: 4 MiniPODs/24 links)
- Interface to Timing, Trigger and Control (TTC) systems. BUSY output.
- Flash memory to store firmware

BCM' - Readout

- When FELIX receives a L0A, the firmware sends out a chunk of data (TBD) around that L0A, it might contain raw data or else, to be defined later
- FELIX is processing the data constantly
  - If there is too much energy in the BCM', it should trigger beam abort
- We have a prototype of the FW for decoding the raw data. We can process it. Could be integrated to ATLAS
  - Abort to be implemented

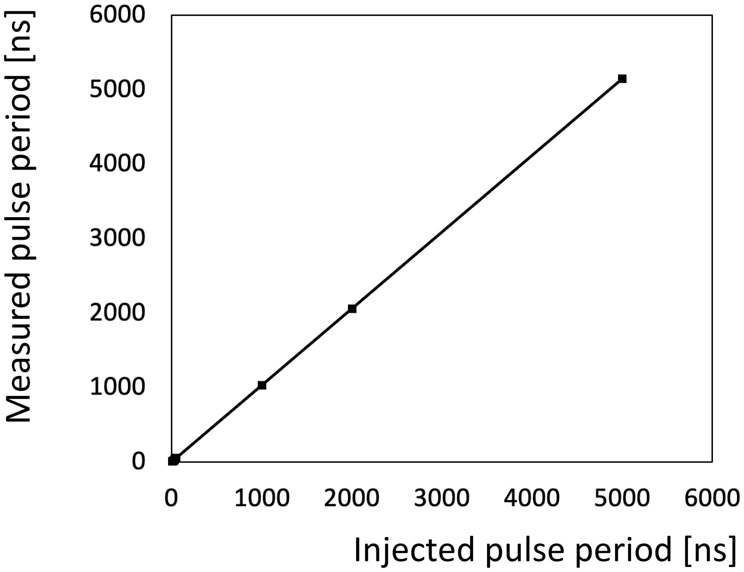


	# E-links
(Differential pairs) E-links per Calypso Lumi	4
E-links per Calypso Abort	4
E-links per module	12
E-links per side	48
Total E-links	96

Read-out channels

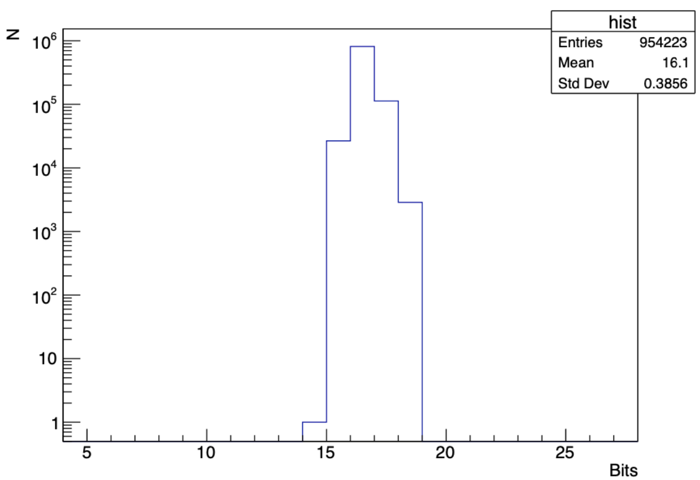
BCM' – FELIX FW

- FELIX based BCM' readout
  - Measurement of ToT and ToA
  - Beam abort and data-taking
  - Final design of the readout structure to be decided: One or two FELIX cards
- Firmware
  - Data-decoder of BCM' semi-digital signals as data-packets
  - I2C commands to configure Calypso
  - Beam abort implementation in progress
- First version of the BCM' FW has presented to FELIX community
- First working prototype completed
  - Official FELIX software libraries in parallel with custom software ROD
- Output word format might change



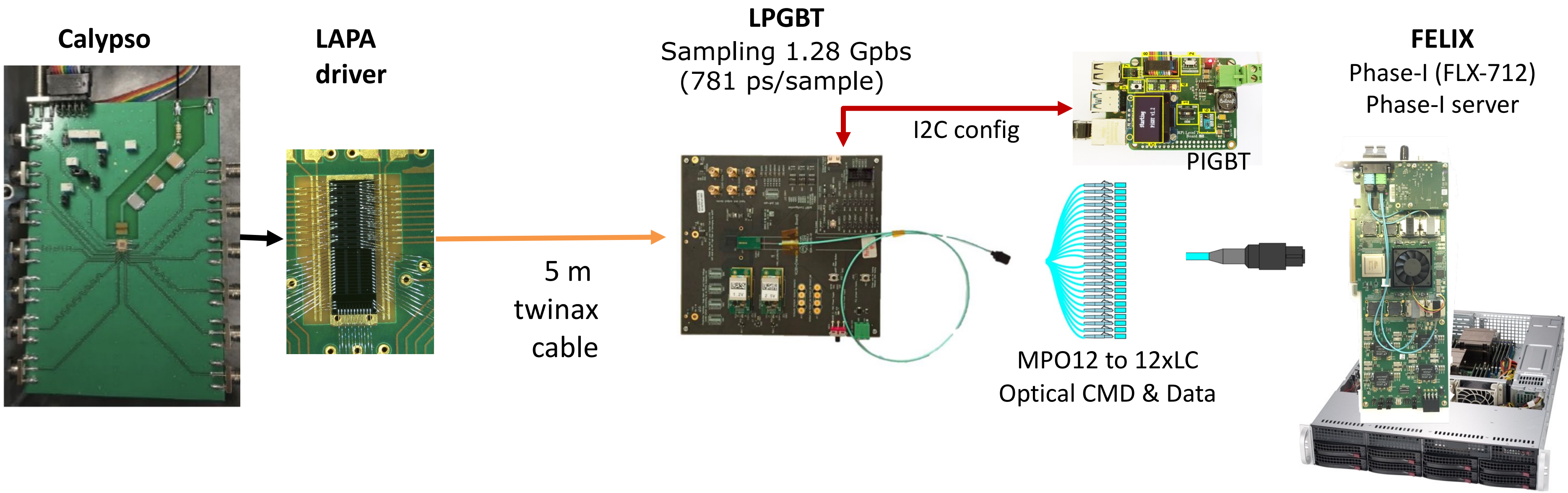
Output Word	L1ID	L1SubID	BCID	ToT	ToA
Number of Bits (32 bit total)	4	4	12	6	6

Output data format

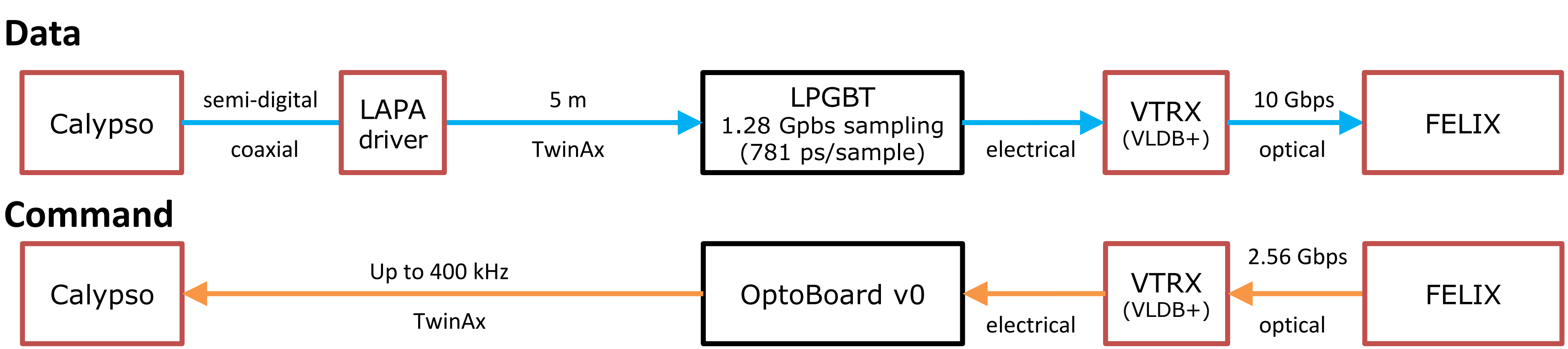


Measured ToA at 80 MHz

BCM' – Basic readout tests

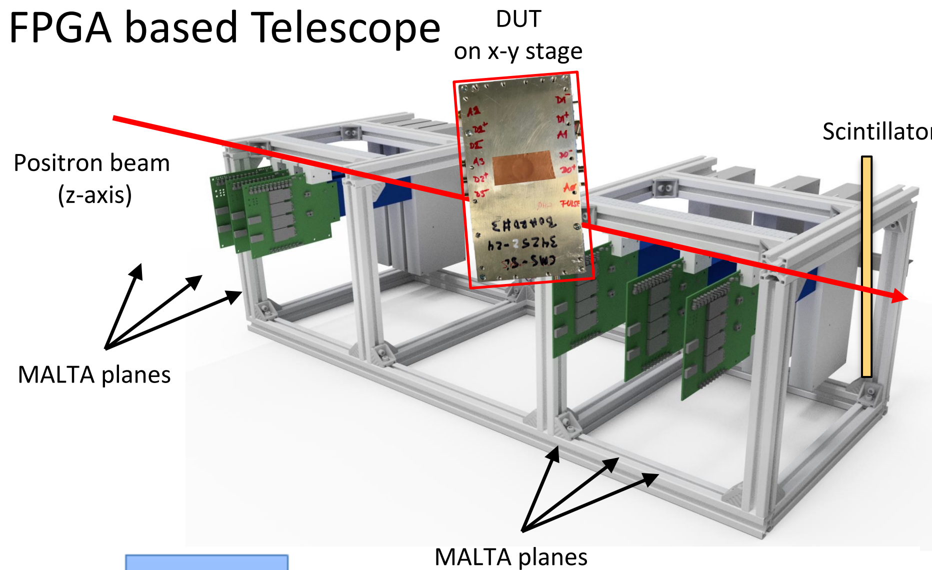


- LAPA driver is used to improve the semi-digital signals over TwinAx cable
- Calypso pulses (not synced to any clock) are recorded by FELIX

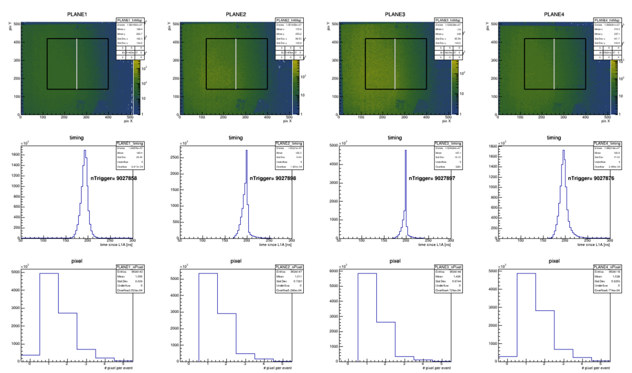


BCM' – Readout test

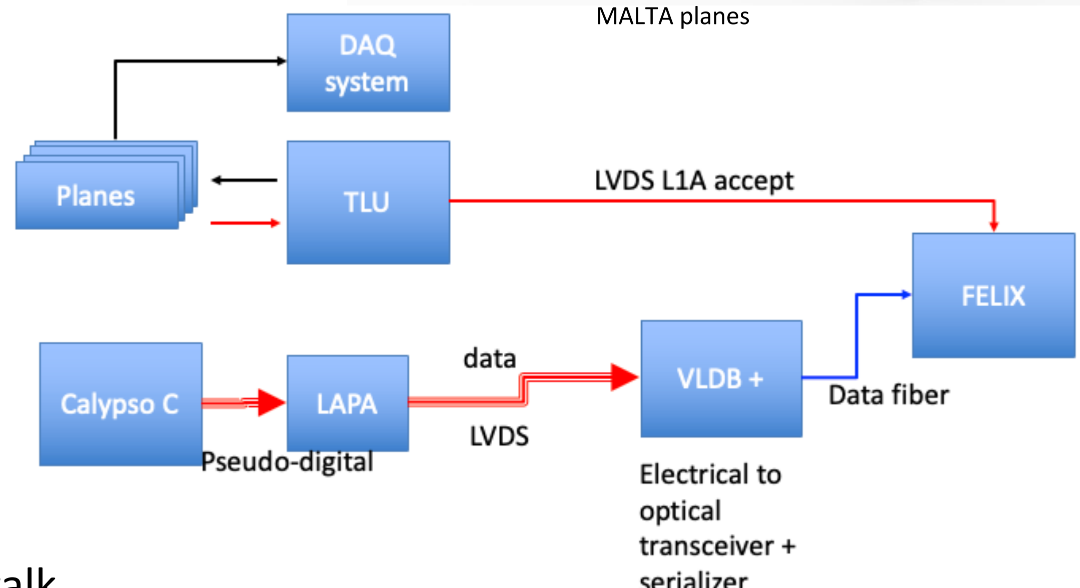
- SPS beam test at CERN with 120 GeV pions used to simulate minimum ionising particles
- MALTA Telescope* - Monolithic pixel sensors FPGA based Telescope
  - Low material content - down to 50um Si



MALTA telescope uses 6 tracking planes + scintillator which give the reconstructed track spatial resolution of 4.1 µm and reconstructed track timing resolution of 2.1 ns



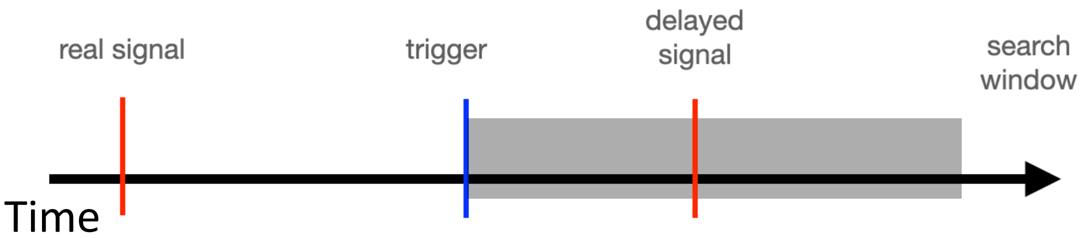
Data acquisition chain
Calypso testbeam measurement testing readout with FELIX using external triggering at high rate (realistic conditions)



* Dedicated slide in Giuliano Gustavino talk

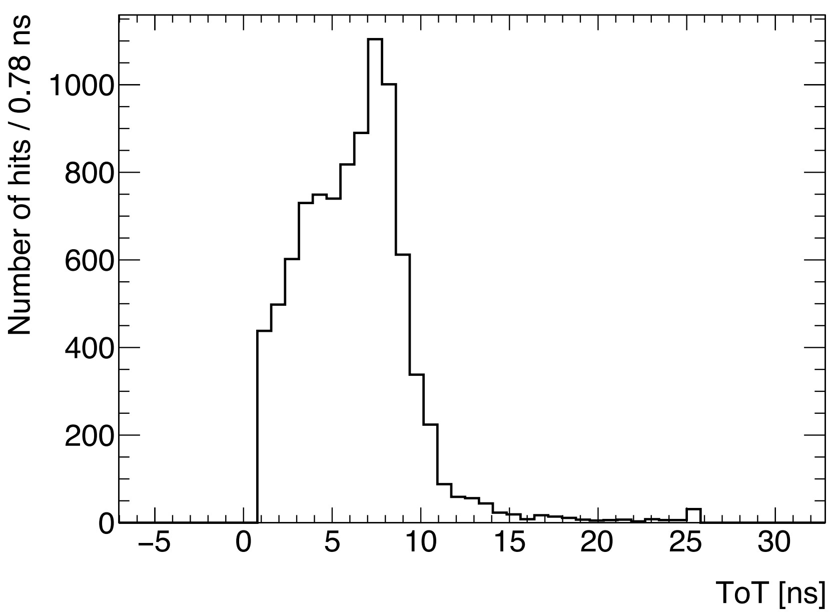
BCM' – FELIX readout

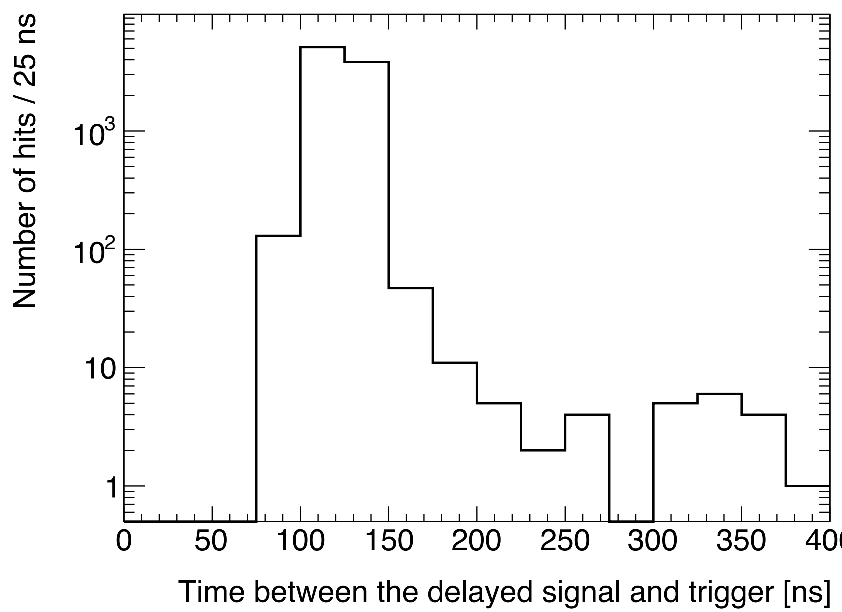
- Preliminary results
- ToT within expected values
- Time between the L1A trigger and the processed signal



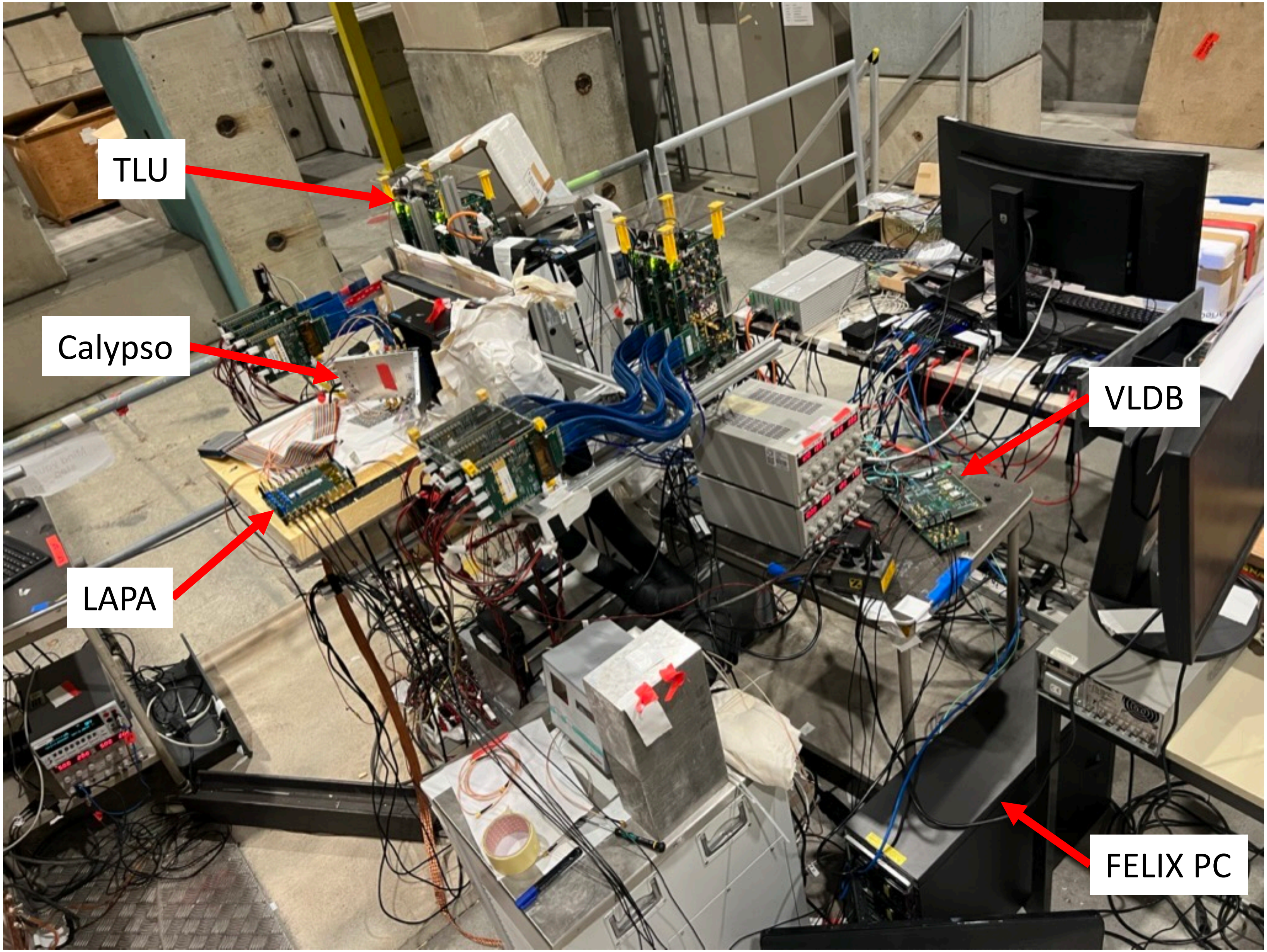
Predictable timing between arrival of data signal and trigger

ToT depends on energy depositon





BCM' – Beam test at SPS (CERN)



Conclusions

- The BCM' detector is currently being developed for the upcoming ATLAS High-Luminosity upgrade
  - It will measure luminosity and protect the inner parts of the experiment
- The design proposal and status have been presented
- Results of Calypso are satisfactory and are within the requirements
- BCM’ first ITK FELIX in beam line
- The FELIX read-out full chain has been presented and tested in a beam line with realistic conditions
- Initial results are satisfactory and withing requirements
  - Read-out chain is able to transmit and process without loss of data
- Missing funcionalitites in the FW will be implemented soon
- Testing of the final modules with the full services will start in 2024

ATLAS ITk BCM'

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Ignacio Asensi, CERN

on behalf of all BCM' Community

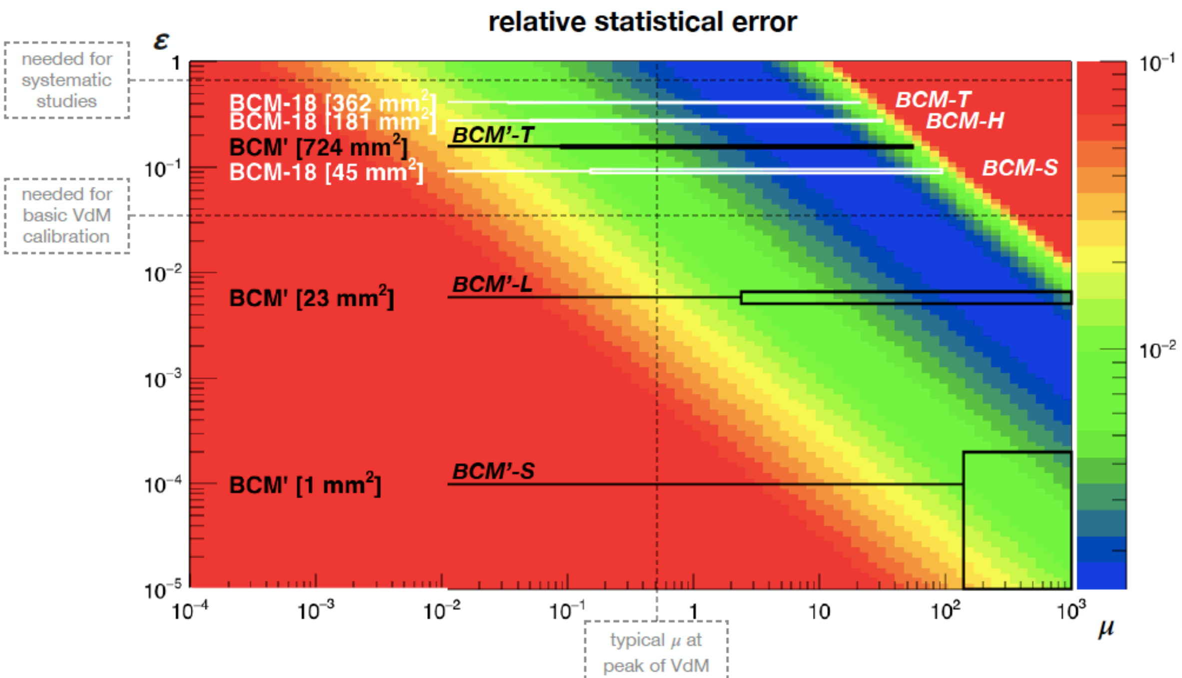
Backup

BCM'

Environment

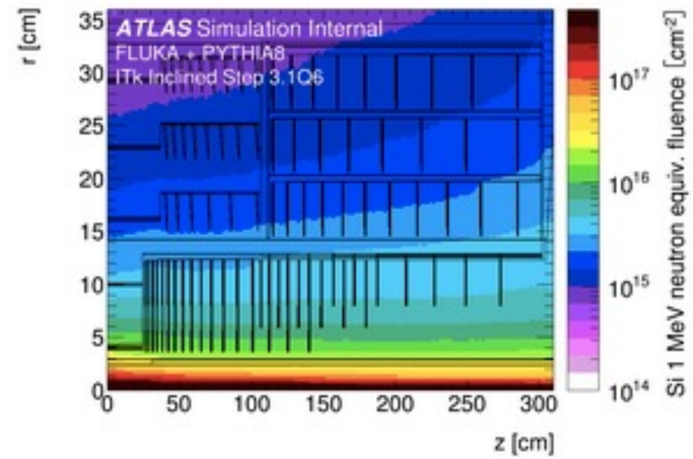
Fluence and dose values for BCM'. Values of 1 MeV fluences and dose are normalised to 2000 fb^{-1}. All other values are per event. **No safety factors have been applied to these values.**

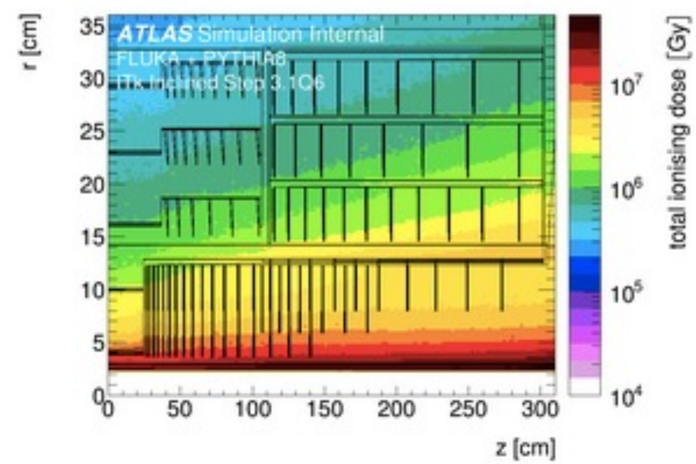
integrated luminosity (fb^{-1})	location	R (cm)	Z (cm)	1 MeV neq (10^{16} cm^{-2})	total ionising dose (MGy)	charged particle fluence (10^{-3} cm^{-2} pp^{-1})	hadrons > 20 MeV fluence (10^{-3} cm^{-2} pp^{-1})
2000	BCM'	9.0	179.5	22.5	1.99	36.3	19.2
	BCM'	10.0	179.5	19.9	1.78	31.8	16.1
	BCM'	11.0	179.5	18.5	1.60	29.1	14.2
	BCM'	12.0	179.5	17.8	1.58	28.6	12.8



BCM' – Radiation environment

- ATLAS radiation simulation, r=9-12 cm, z=1.8 m
- NIEL&TID for 2/ab, nominal -> x1.5 safety factor
  - TID $\lesssim$ 200 Mrad -> 300 Mrad
    - Services: max. at PP1(Type1/2) – 300(450) Mrad
  - NIEL ~$2x10^{15}$ n_{eq}/cm^2 -> $3x10^{15}$ n_{eq}/cm^2
    - low neutron fraction
    - n_{eq} for diamond ? -> take $3x10^{15}$ 800 MeV p/cm^2 for sensor benchmark
  - Charged particle flux/BX @10 cm
    - ~$0.032/cm^2$ x μ (50% e^+e^-)
    - ~$4.5(6.4)/cm^2$ for μ = 140(200)
    - hadron flux (SEE) ~$2.3(3.2)/cm^2$
- Flux ~140(200) MHz/cm^2 -> 70(100) MHz/cm2 SEE flux
  - May 2022: Test @ CERN HiRadMat facility to verify high-rate response for *lumi* and *abort* – talk by Andrej





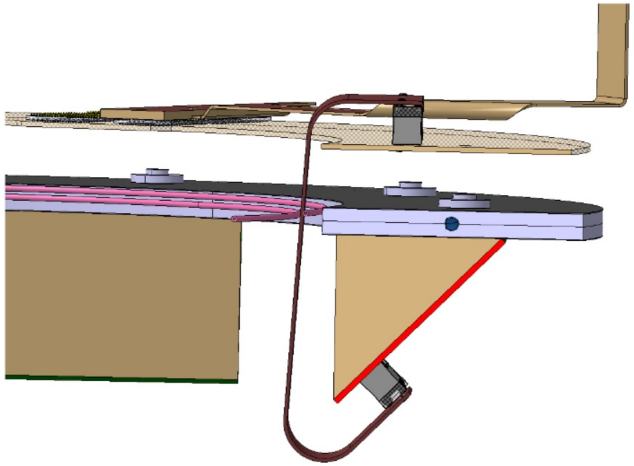
BCM' - Functionality

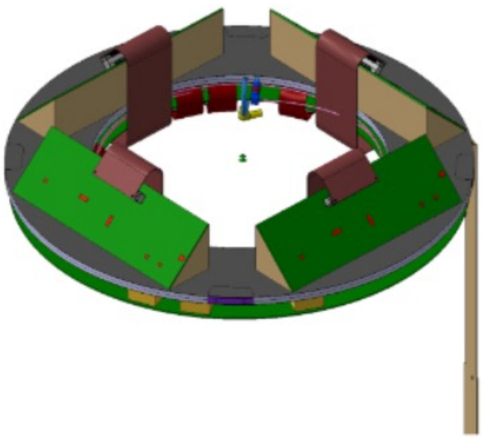
- Beam protection - *Abort*
  - ***out-of-time*** signals (~6 ns *before* collision) mean upstream *non-collision background* (NCB)
  - abort on *out-of-time* activity above (large) threshold signifying beam background at ITk danger level
    - danger thresholds can be high (now SCT 25k/cm^2/BC i.e. 4000x the lumi induced signal)
  - need to **keep flexibility** for threshold settings
  - include machine-style (slow, 40 µs integrating) Beam Loss Monitor (BLM)
- Luminosity measurement and NCB - *Lumi*
  - lumi main algo: (absence of) ***in-time*** (~6ns *after* collision) signals (*r* - zero counting) -> single MIP sensitivity
  - ideally have to cover μ-range from VdM (0.01 in tails) to μ=200 (ultimate HL-LHC lumi) in a lumi block
  - 1% limits in 60 LHC seconds vs. μ shown for sensor sizes at foreseen location, all sensors cover ~10 cm^2
  - comparison to current BCM': factor ~7 less sensitive per unit surface
    - ~2 for larger radius
    - ~3.5 for less conversions (less material !)
  - NCB: *out-of-time* signals at (multi)-MIP level

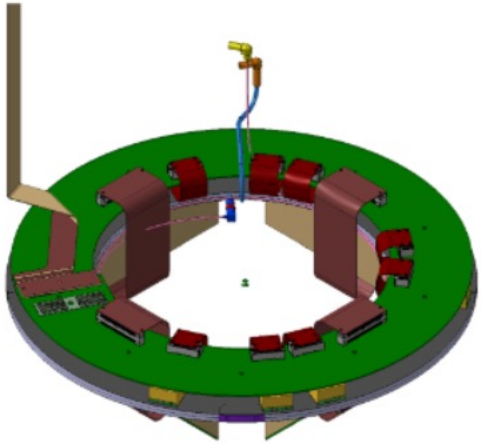
BCM’ – Module

- The enclosure of the whole package of the BCMp station, including the aPCB
- Evaluated together with the rest of the ITk CAD
- The current design fits in the allocated space between the rings.

Detail of the aPCB (top) and the BCMp station (bottom)

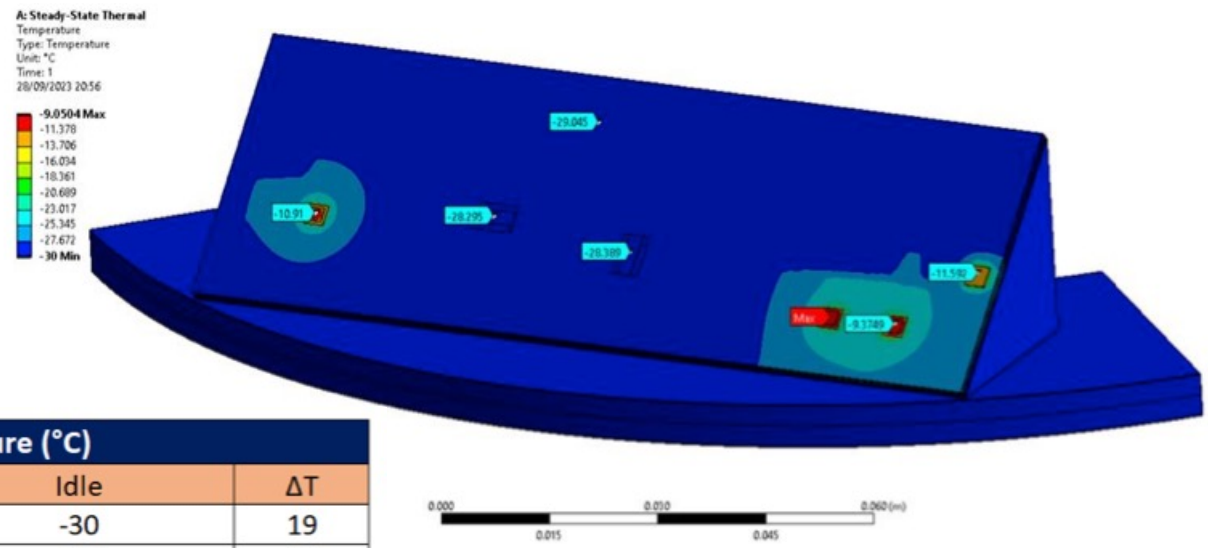






Bottom (left) and top (right) 3D models of the BCMp station including the aPCB ring

BCM' – Thermal



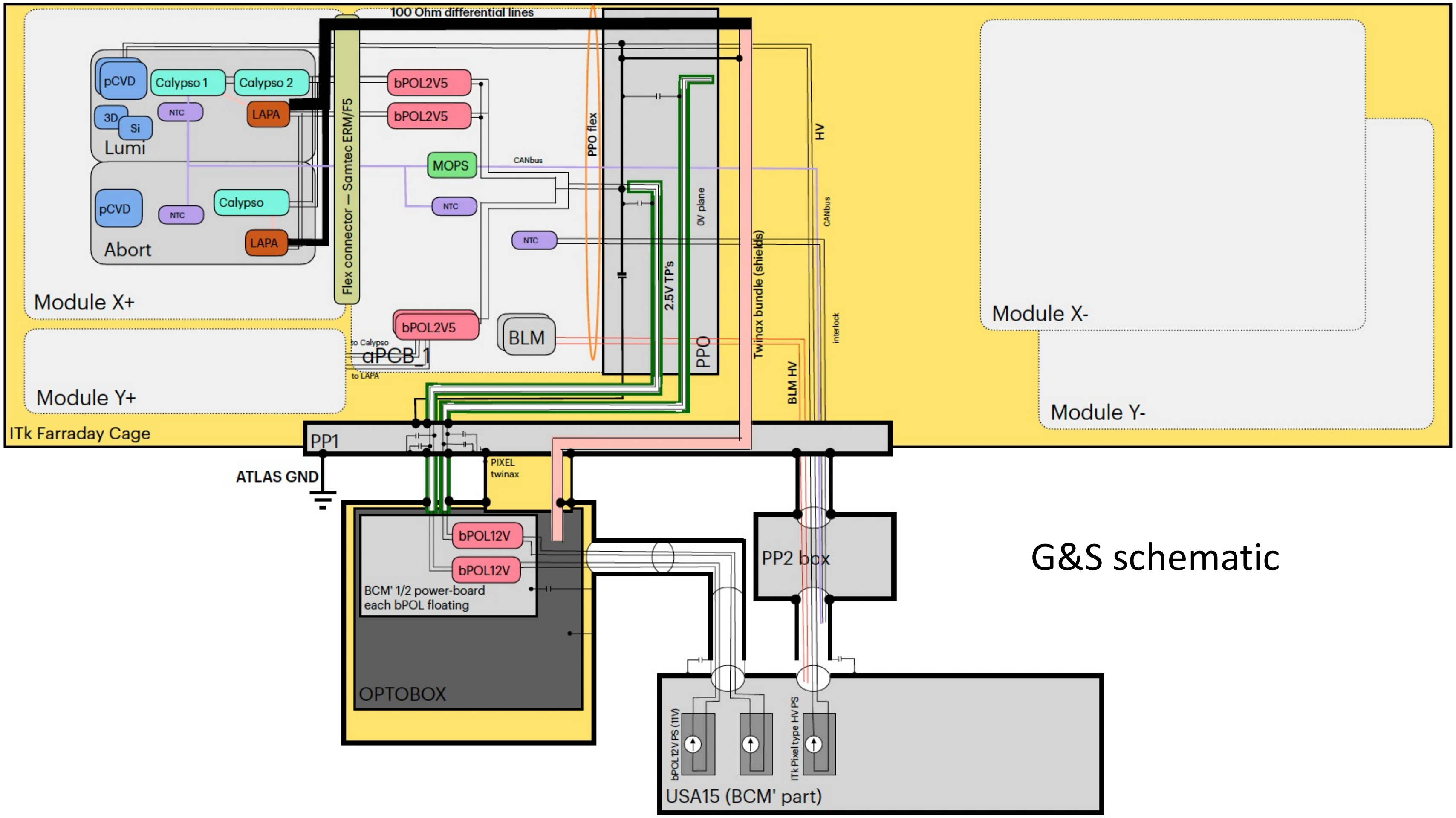
Temperatures obtained, in load and idle

Model results - Temperature (°C)			
Chip	In load	Idle	ΔT
Calypso 1	-11	-30	19
Calypso 2	-9	-30	21
Calypso 3	-9	-30	21
LAPA 1	-28	-29	1
LAPA 2	-28	-30	2
Si diode	-12	-29	17

Temperature distribution obtained after simulation

- PCB's composition/thermal conductivity is by far the most important parameter of the simulation, we observe a temperature gradient of less than 2°C between the cooling fluid and the top surface of the wedge
- Critic components of the module are the Calypso chips, in terms of thermal performances/risks
- Convection has a minor effect on cooling with respect to the cooling fluid, in this range of temperature
- The model is probably too conservative, as the current PCB model does not include the thermal vias that are present on the real module yet

BCM' – Grounding and shielding

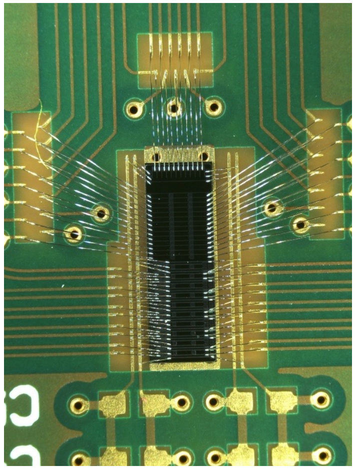


G&S schematic

LAPA

LAPA, a 5 Gb/s modular pseudo-LVDS driver in 180 nm CMOS with capacitively coupled pre-emphasis

- In the nominal condition with a steering current of 4 mA over a 100 Ω termination resistor, it consumes 30 mW from a 1.8 V supply
- LAPA can drive up to 6 mA, in the nominal condition with a steering current of 4 mA over a 100 Ω termination resistor, it consumes 30 mW from a 1.8 V supply with an input clock of 2.5 GHz



- 10 In/Out CMOS/LVDS channels
- CHIP input configurable CMOS/LVDS
- Channel output configurable CMOS/LVDS
- Power Supply 1.8V
- Internal Input termination resistor 100Ω
- Tuneable LVDS pre-emphasis
- Configuration pads with internal pull-up, all active high
- LVDS OUTPUT with selectable VCM internal feedback

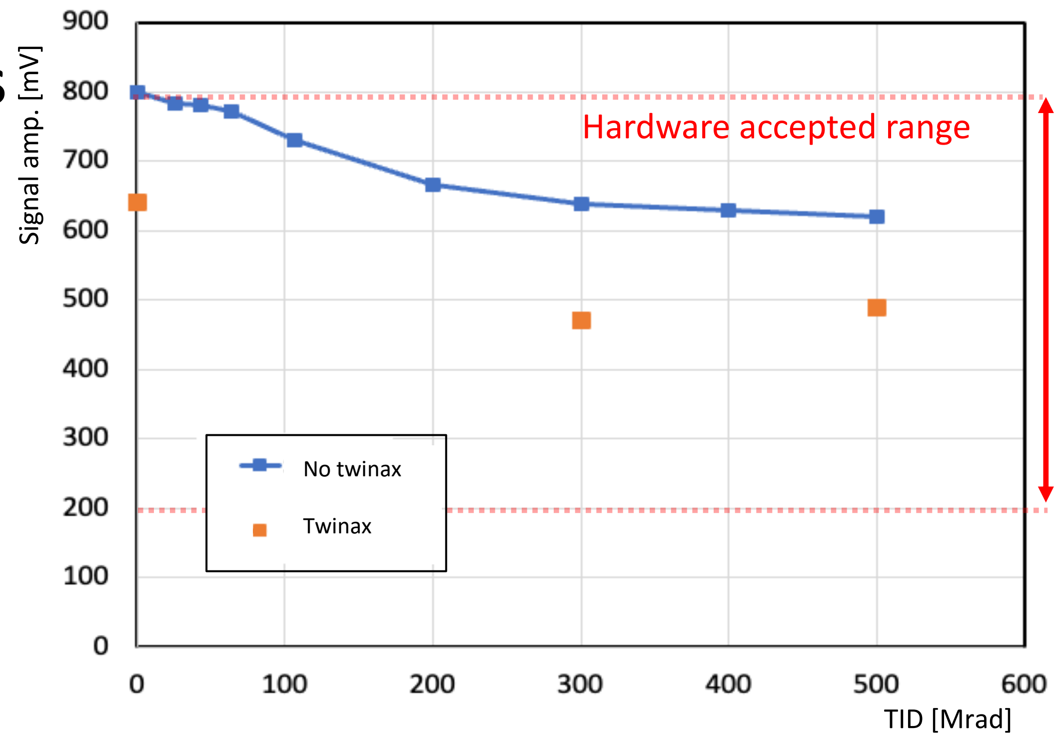
SPEC	Min	Max	Tested
VCM	0.7 V	1 V	0.75 V
Vdiff	0.3 V	-	0.4 V
Term Res	-	-	100 Ω
Bit rate	-	-	5 Gbit/s

Power	Current [mA]	Power [mW]	Input
Static	2.69	4.84 V	-
Dynamic	-	0.44	5 Gb/s
Total	-	5.28	5 Gb/s
Bias Static	0.94	1.7 V	-
RX+Bias	-	6.98	5 Gb/s

Documentation - https://cds.cern.ch/record/2312590?ln=en
TWEPP - https://pos.sissa.it/313/038/pdf
TID measurements - https://twiki.cern.ch/twiki/bin/view/Atlas/Malta2PublicPlots#MALTA2_vs_TID

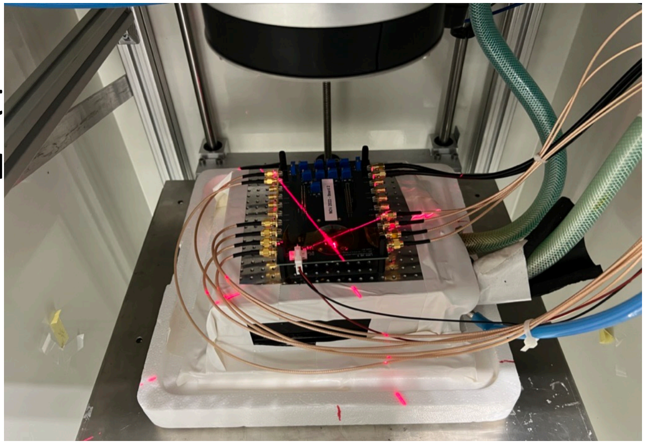
LAPA driver irradiation at CERN

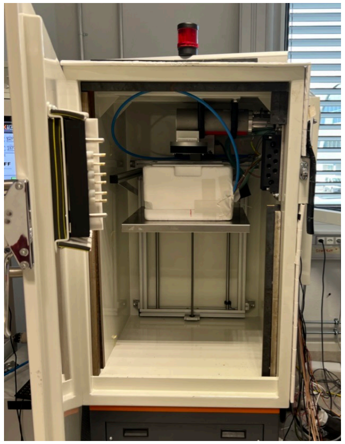
LAPA, a 5 Gb/s modular pseudo-LVDS driver in 180 nm CMOS



- **LAPA irradiated to 500 Mrad.**
- **Cooled at -10℃**

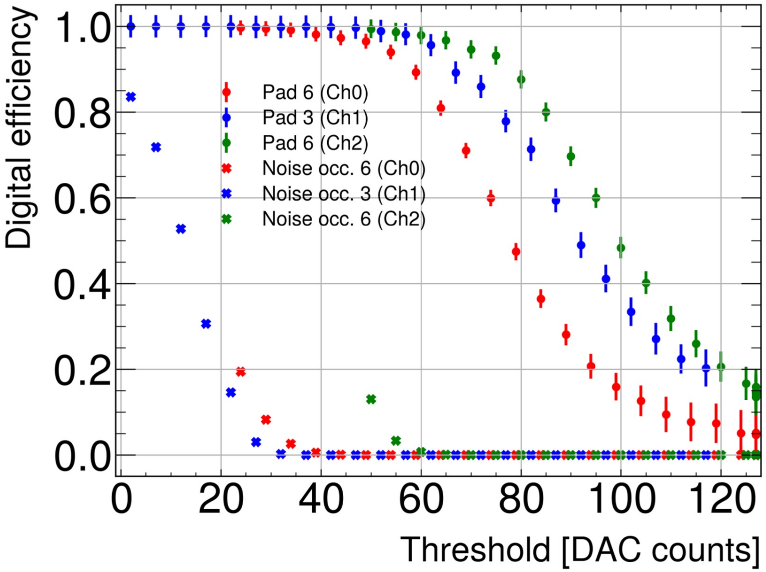
- Signal amplitude and rise time are affected by radiation but digital readout still 100 % operative
  - Well within required range for differential signal
- Measured ToT and ToA values remained constant
- Performance with Twinax is t
- Small change in power consu from 37.7 mV to 35.6 mV



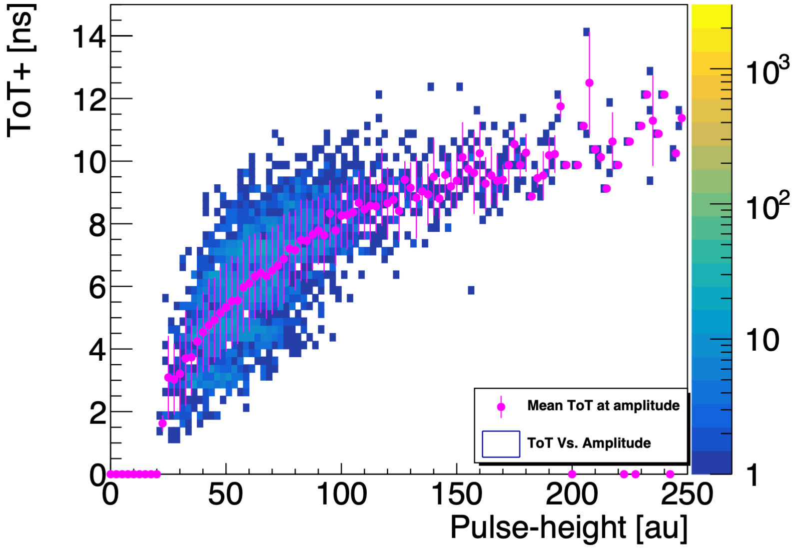


BCM' – Calypso efficiency

Calypso ver. C, S8 pCVD diamond, Cr/Au met., -1000 V

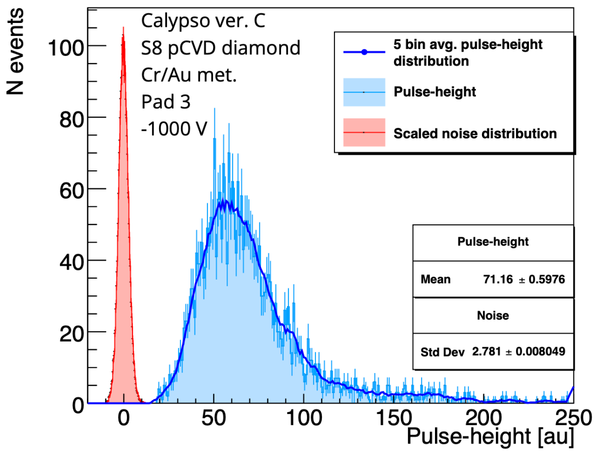


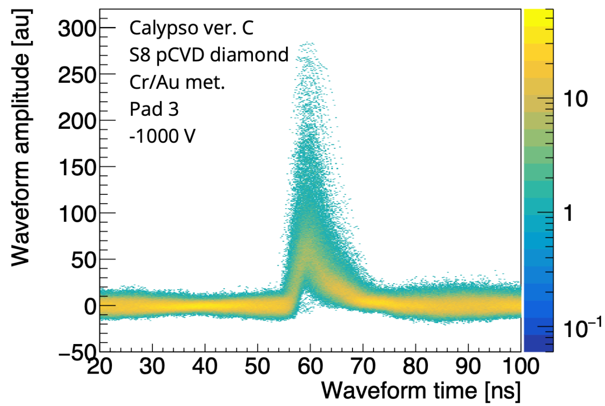
Calypso ver. C, S8 pCVD diamond, Pad 3, Cr/Au met., -1000 V, CFD threshold 52 DAC

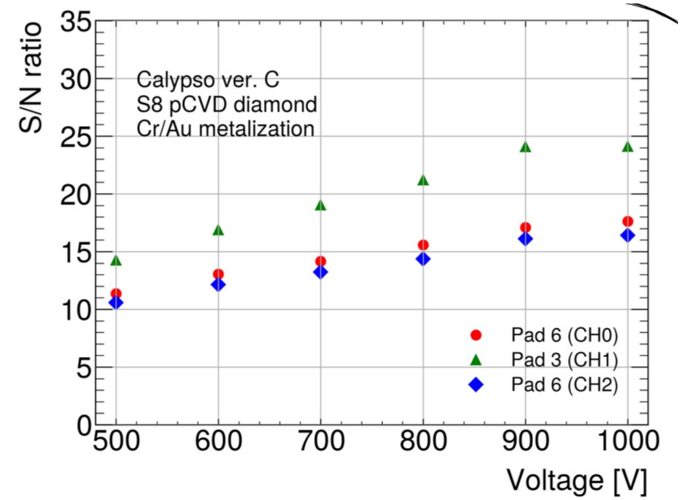


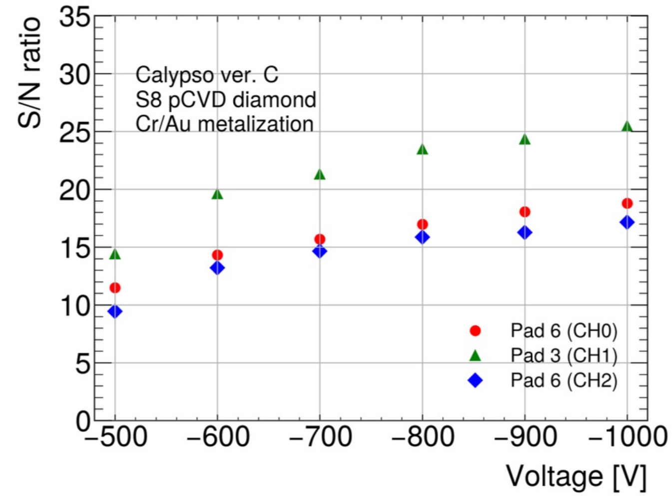
- Threshold scan shows Calypso ASIC can be run at variable efficiency and low noise occupancy for all three tested detector channels. The Calypso ASIC ver. C tested here featured a smaller range of 128 CFD threshold steps of ~100 - per step. For each individual threshold setting we measured the expected distribution of ToT vs. pulse-height for events triggered by the CFD.

BCM' - Signal to noise



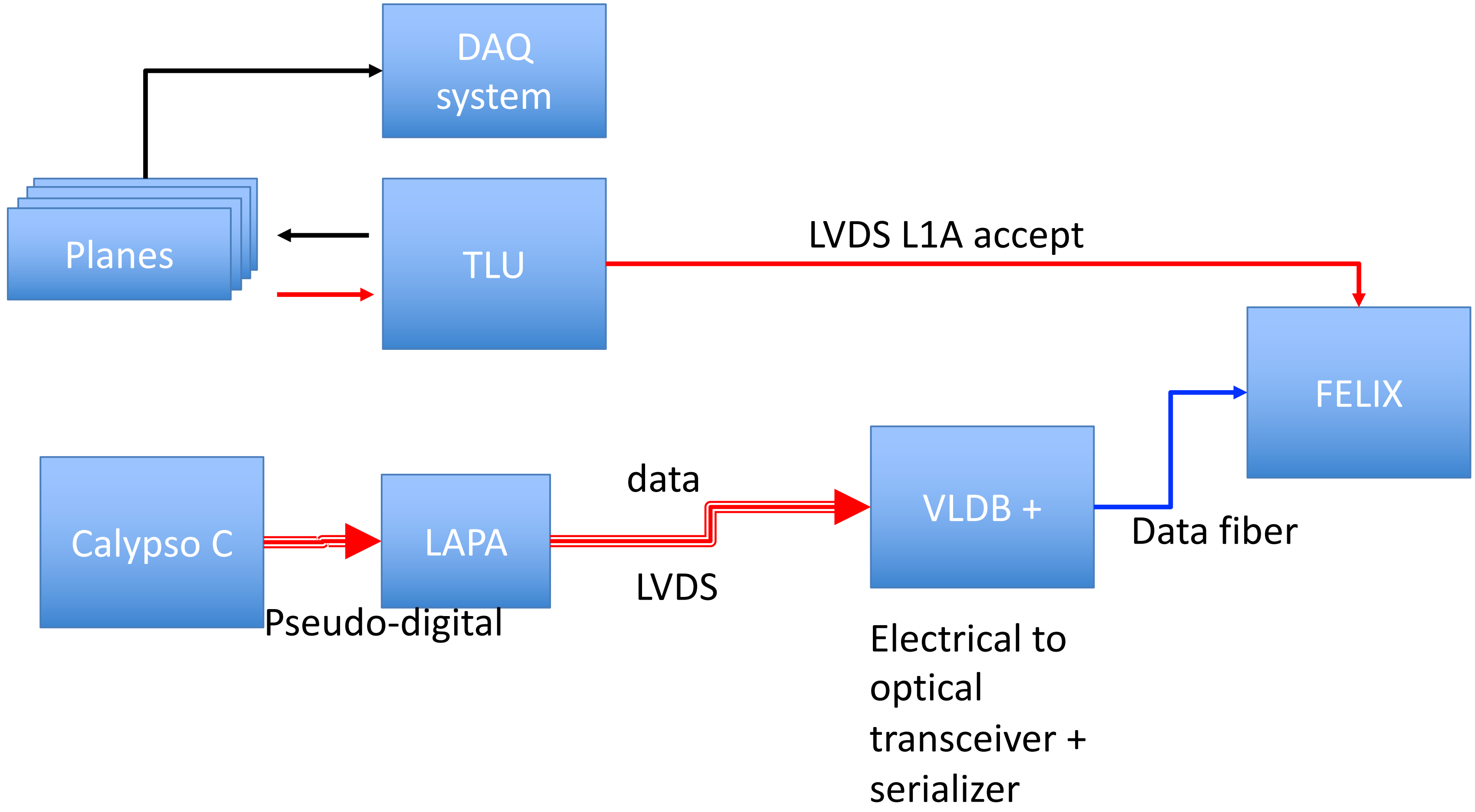






- Analog output signal to noise ratio of 25 measured for Pad 3 at bias voltage of ±1000 V.
- The system can reliably achieve S/N ratio >20 at ±800 V bias voltages.

BCM' – Readout test



BCM' – Beam test at H6 line SPS (CERN)