Development of the BCM' system for beam abort and luminosity determination at the HL-LHC based on polycrystalline CVD diamond

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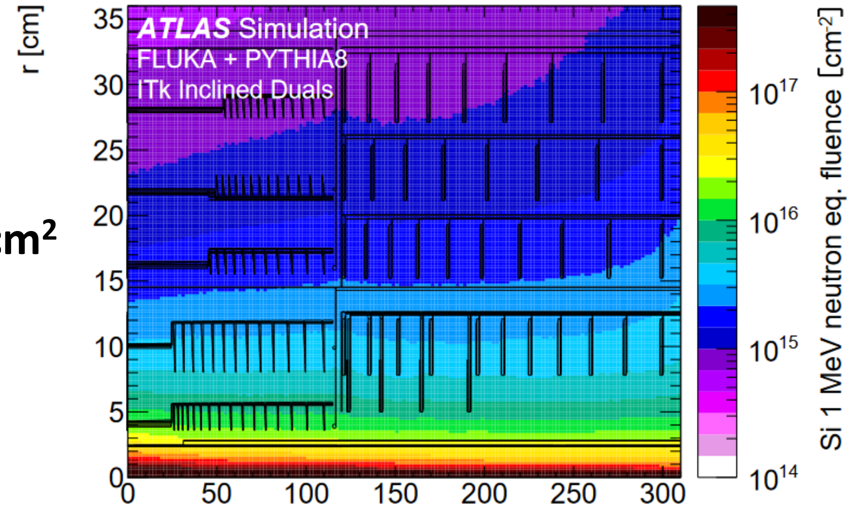
on behalf of BCM' collaboration

ATLAS Beam Conditions Monitor

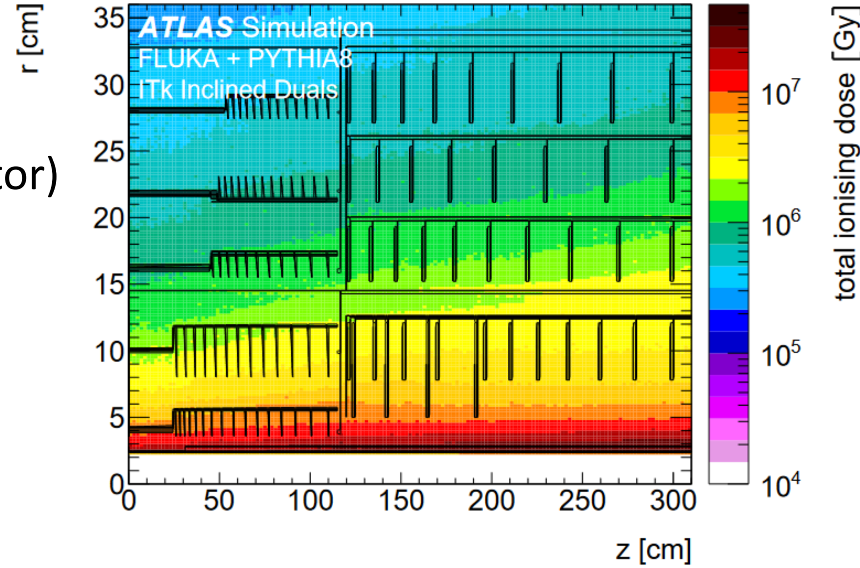
- Beam Conditions Monitor (BCM) in ATLAS at the LHC:
  - Installed since 2008
  - Located in the Pixel Detector at *z = ± 184* cm, *r = 5.5* cm
  - Based on radiation tolerant diamond sensors
    - **NIEL 1 x 10^{15} n_{eq}/cm^2, TID 50 Mrad**, charged particle flux up to **60 MHz/cm^2**
- BCM provides bunch-by-bunch detection for **Beam Protection and Luminosity measurement:**
  - Per-bunch fast safety system *(abort)*
  - Background monitoring
  - Per-bunch luminosity meter (*lumi)*

Can abort LHC beam to protect the tracking detector

- HL-LHC: particle density will increase by an order of magnitude
  - Charged particle flux up to **160 MHz/cm^2** at pile up **μ = 140**
  - **NIEL 3 x 10^{15} n_{eq}/cm^2**, **TID 300 Mrad** after **2000 fb^{-1}** (including x 1.5 safety factor)
  - A new **BCM'** system will be installed in ATLAS ITk in 2024
  - BCM' collaboration: OSU, JSI, Manchester, Wiener Neustadt, CERN



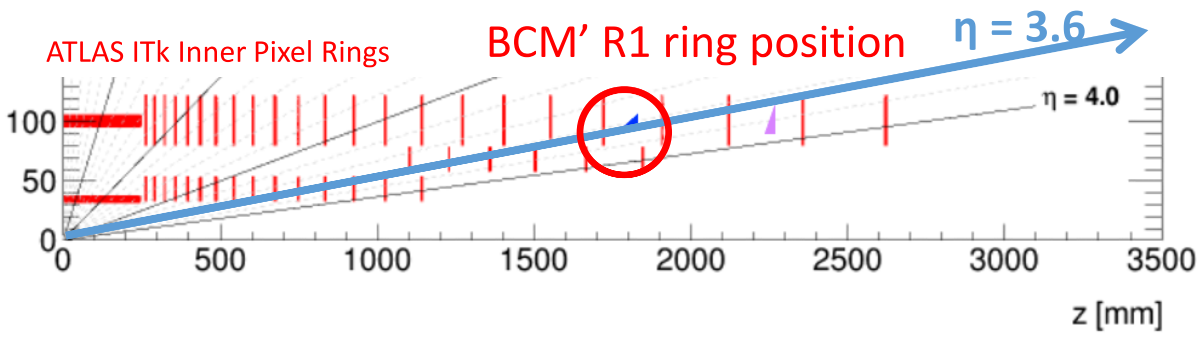
[ATLAS ITk Pixel TDR]

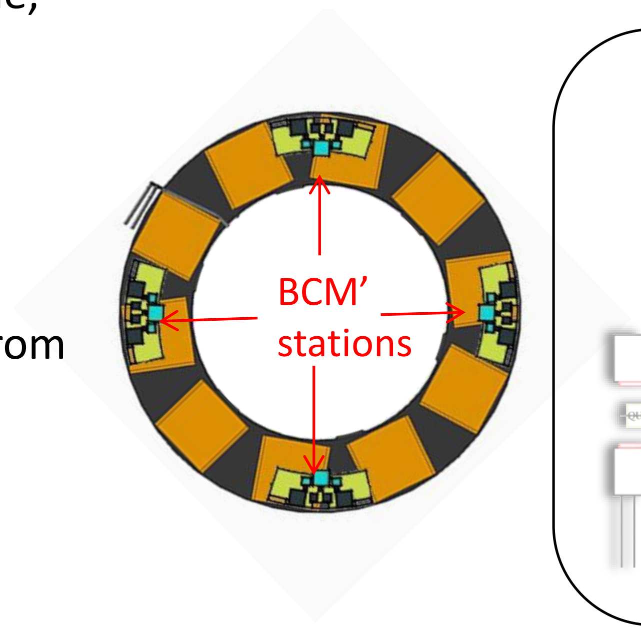


BCM' overview

- Located at r = 100 mm, *z* = ± 1800 mm (6.25 ns) from Interaction Point on both detector sides
- Collision/background separation based on Time of Flight
  - **Luminosity:** **Collision products** arrive simultaneously on both detector sides (in-time)
  - **Beam protection:** **Background** arrives out-of-time, 12.5 ns delay between two sides
- Four stations per each side of the detector
- Multiple detectors by function
  - Abort (dynamic range > 10^5 MIP)
  - Beam Loss Monitor (BLM) – electronics copied from LHC machine (slow, integrating)
  - Luminosity (single MIP sensitivity)

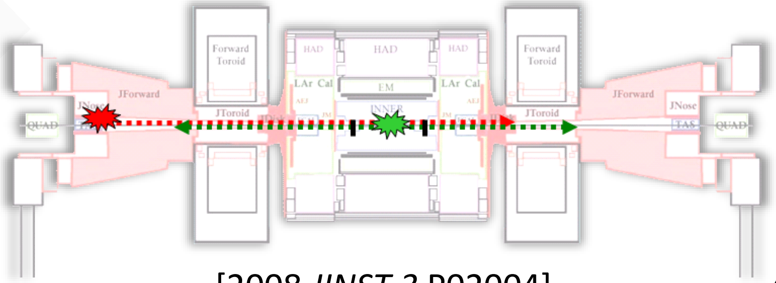
Each with own sensor





BCM TOF concept

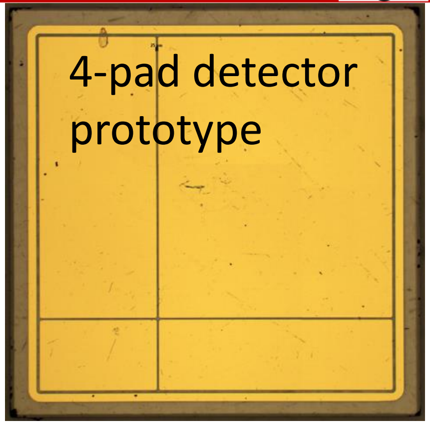
- **Collisions: in time**
- **Background: out of time**

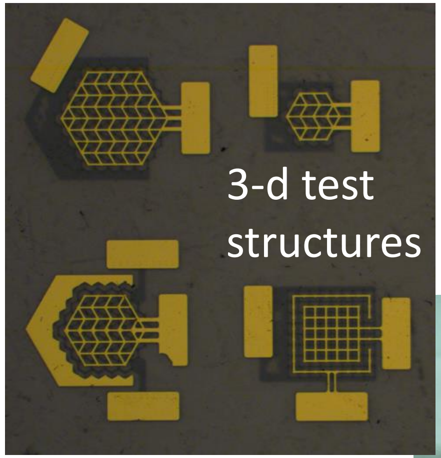


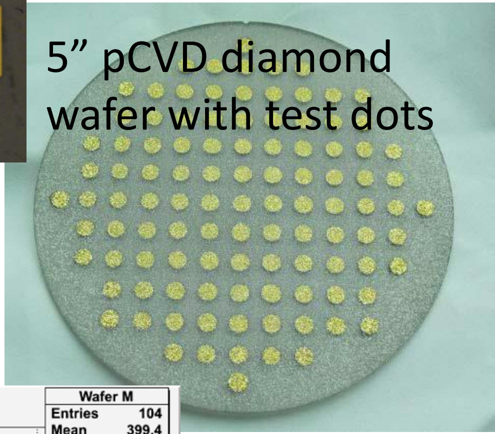
[2008 *JINST 3* P02004]

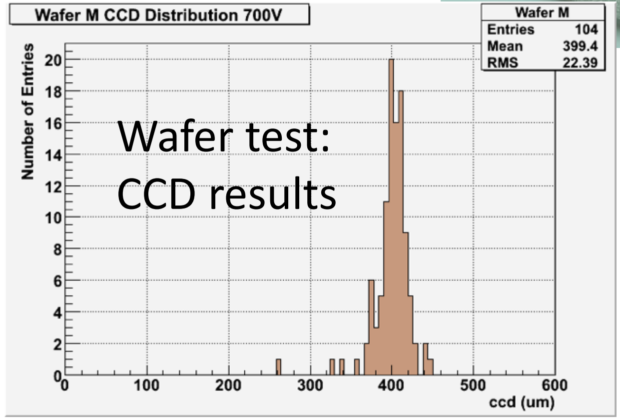
BCM' sensors

- Sensitivity on very broad range of particle fluxes required
  - Four orders of magnitude, $\mu_{vdM} = 0.01$ → $\mu_{ultimate} = 140$
  - Dynamic range flexibility by segmenting the sensor into pads of varying size
- Three types of *polycrystalline chemical vapor deposition* (pCVD) diamond sensors and one silicon sensor per station:
  - **10 x 10 mm²** (lumi), three pads (size 1 mm² – 50 mm²)
  - **5 x 5 mm²** (abort), four pads
  - **1 x 1 mm² 3D** (lumi), single pad, hex or square electrode cells (53 µm sense-to-field electrode spacing), C = 5 pF, highest radiation tolerance
  - Small **Si pad/strip** (lumi), 10 mm², 5 pF
- Diamond sensors produced by US vendor II-VI (worked with RD42)
  - Three 500 µm thick 5-inch wafers have been grown for the project
  - Prototypes delivered Dec 2021
  - Promising first measurements of charge collection, long term current stability
- SPR and PDR passed for sensors, FDR/PRR early 2022



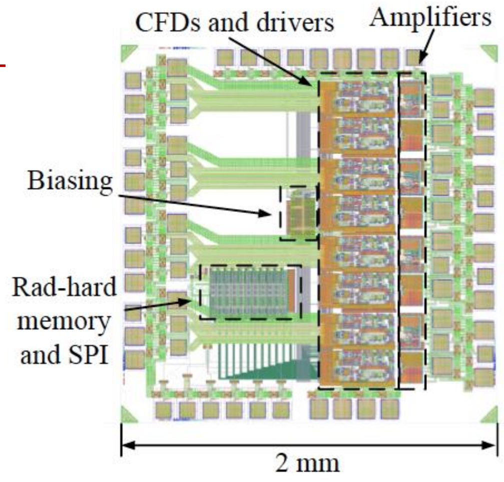






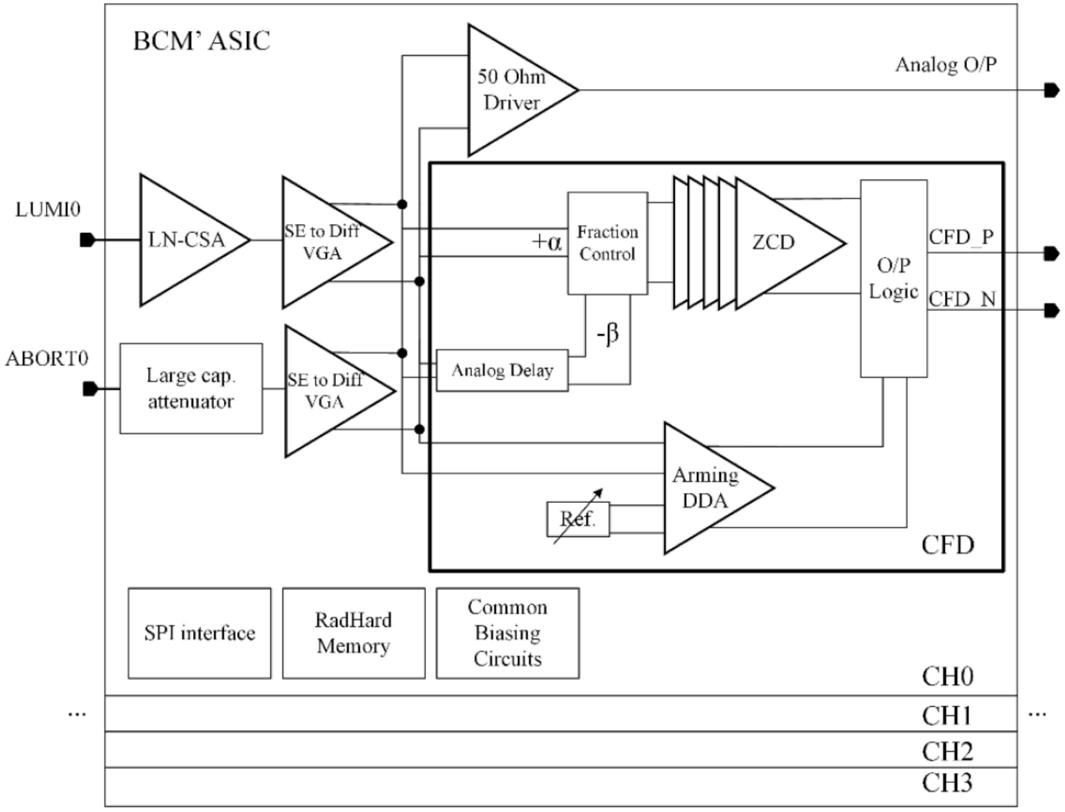
BCM' Front End - Calypso

- Calypso: New custom 4-channel front end ASIC
  - TSMC 65 nm process, MPW
  - Reticle size 2 mm x 2 mm
  - Two (mutually exclusive) input options per channel: *lumi/abort*



CALYPSO specifications:

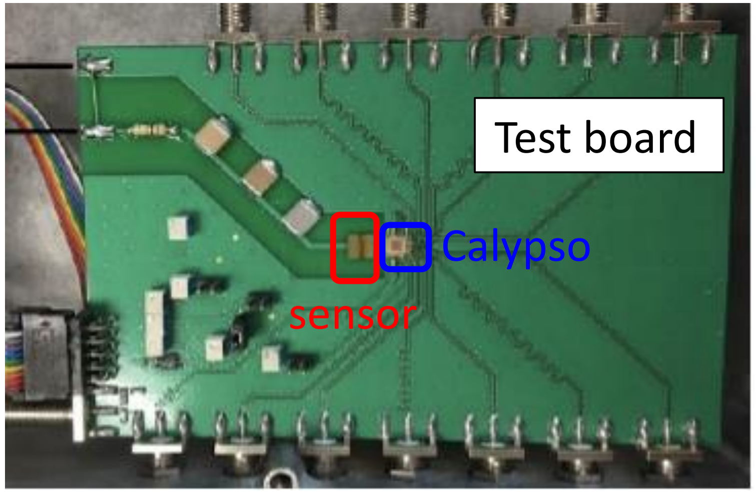
- Optimized for **C_{det} 2–5 pF**
- **t_{peak} < 1.5 ns, $t_{settling}$ < 15 ns** (at C_{det} = 2 pF)
- **σ_{jitter} < 100 ps** (at C_{det} = 2 pF for > 3.6 ke$^-$ signals in simulation)
- ***lumi***: ± 50 ke$^-$ dynamic range, (110 + 55/pF) e$^-$ noise gain 55 mV/fC
- ***abort***: ± 750 Me$^-$ dynamic range, 830 ke$^-$ noise, gain 8.2 µV/fC
- **digital LVDS output**, analog preamp output for testing

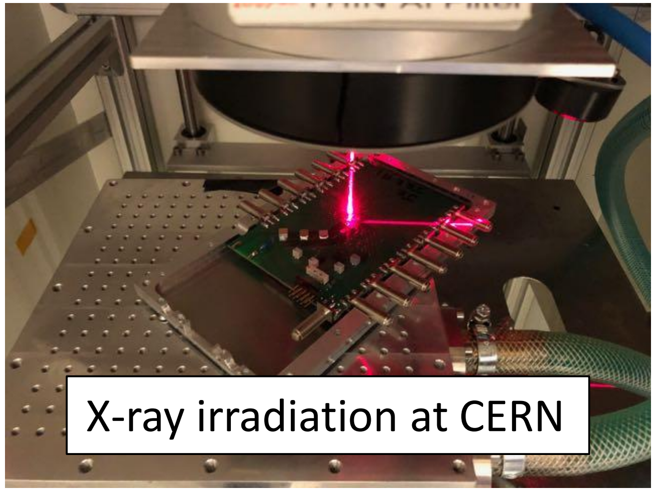


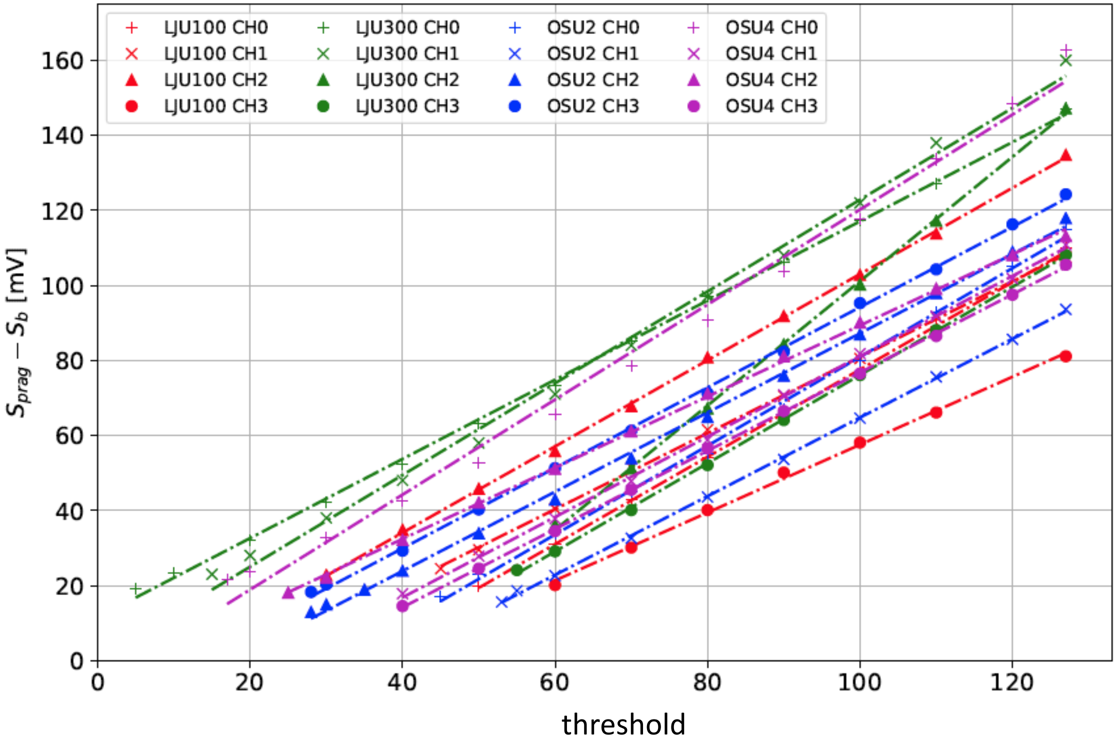
- 3rd iteration Calypso_C received Dec 2020
- 4th planned for June 2022
- ASIC FDR early 2022, PRR early 2023

Calypso_C Bench Tests

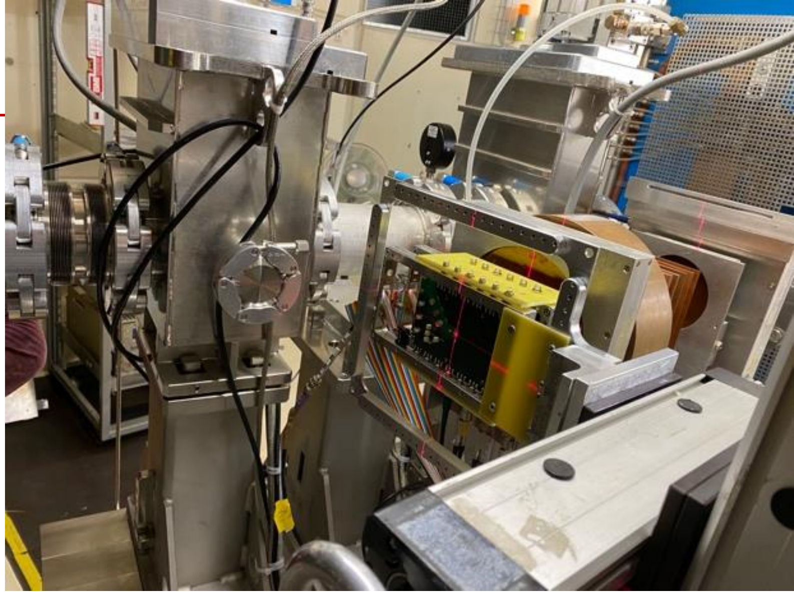
- Single chip test boards assembled at OSU and JSI
- Basic functionality test ok
  - Except (much) larger threshold offset spread than expected from simulation
  - Consistent results at OSU and JSI
- Chips irradiated up to 300 Mrad X-ray (unpowered)
  - Functional after 300 Mrad
  - < 20 % of variation on analog parameters observed
  - Need to irradiate powered and cold (counter-effects!)
- I²C for chip configuration fully tested







Single Event Effects tests at PSI with Calypso_C

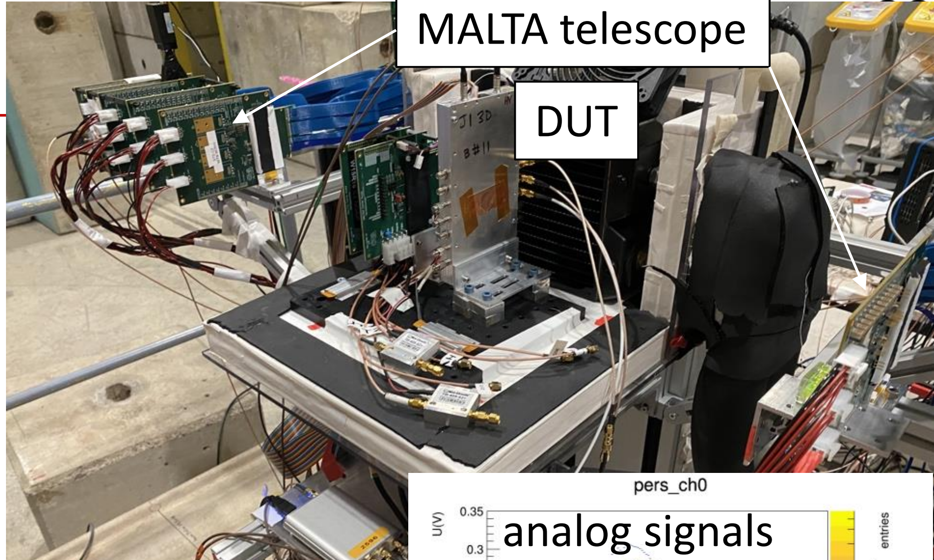


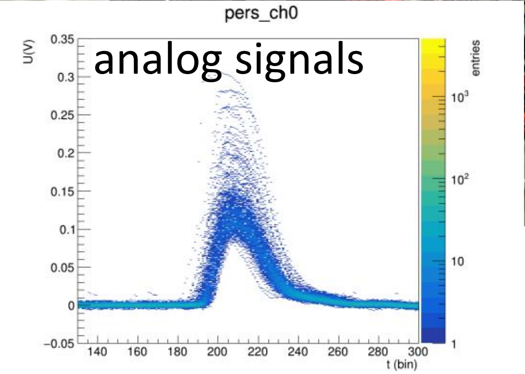
- Test 1 at PiM1 at PSI (Aug 2021), 260 MeV/c pions (4e11 pions/cm^2 total)
  - **Unirradiated** Calypso_C
- Test 2 at PIF at PSI (Oct 2021), 230 MeV protons (3.5e13 p/cm^2 total)
  - **Unirradiated** Calypso_C and Calypso_C irradiated with **300 Mrad** (X-ray)
- Test procedure:
  - Triple Modular Redundancy (TMR) register cells with active feedback
  - 30 8-bit registers i.e. 240 bits loaded with a binary pattern, read out every 10 s
  - If change observed reload and re-start reading
- Pions:
  - 4 “events” observed, strange patterns due to readout interface errors
  - Readout issues fixed for subsequent test
- Protons:
  - No events observed with unirradiated chip
    - Rate consistent with ITk strips upper limit 1e-14 cm^2
  - Two events observed in chip irradiated to 300 Mrad →
    - TMR logic probably at edge of functionality
    - Not problematic, since registers can be written at will

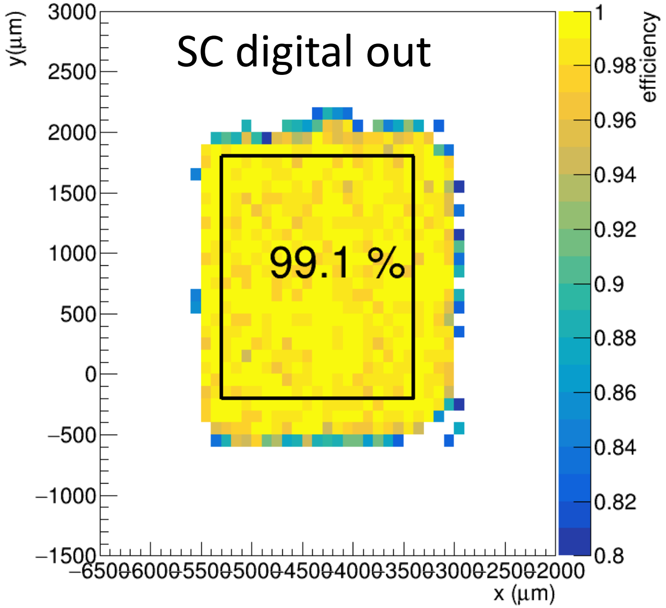
1111 1111 → 1111 1101
0010 1100 → 0100 1100

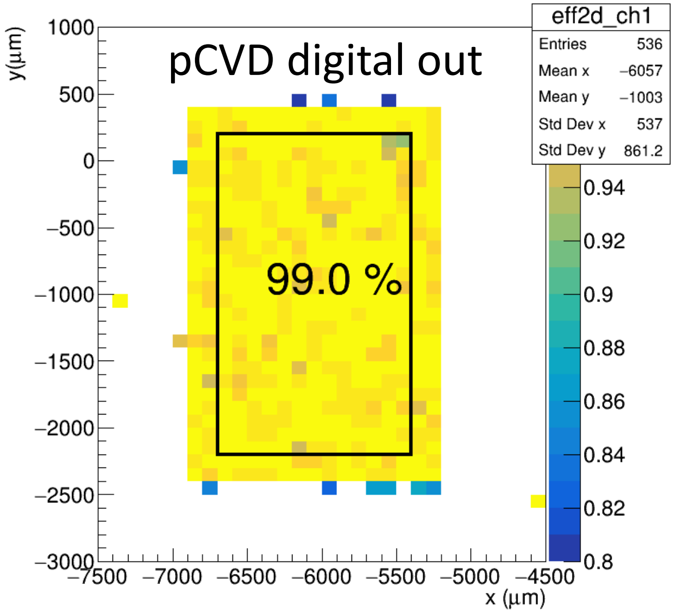
Test beam at CERN SPS

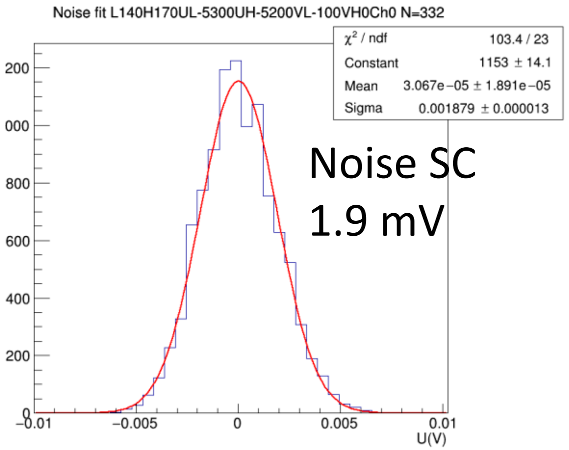
- Test beam in Oct and Nov 2021 with refurbished diamond sensors (5y old)
- 120 GeV pions, MALTA CMOS telescope
- Read out analog and digital signals with DRS4 oscilloscope
- Single crystal and pCVD diamond samples (unirradiated)
- Analysis still ongoing
- Efficiency above 99 % with digital signals in both samples

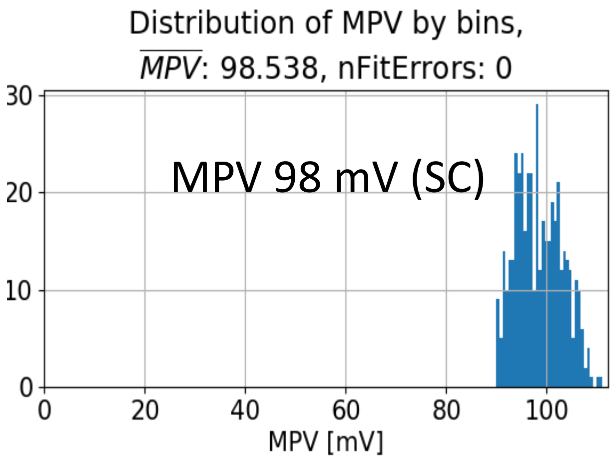












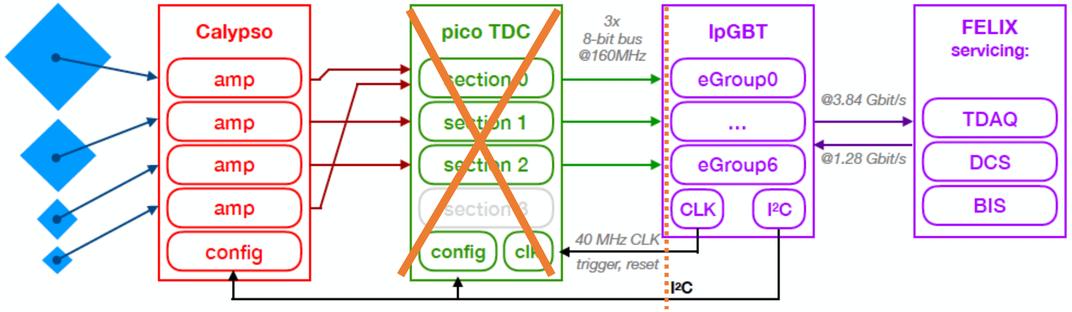
BCM' readout

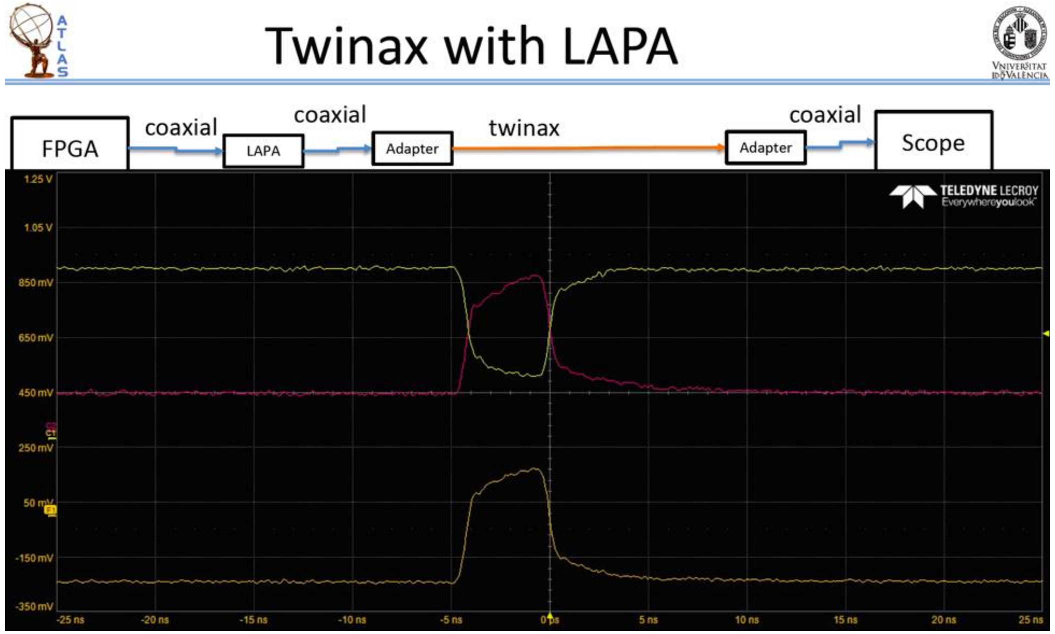
- Original baseline was

Calypso → picoTDC (digitization) → lpGBT (to optical) → FELIX

  - Use of picoTDC abandoned due to delivery, radiation issues
  - lpGBT on opto-panel (lower radiation environment)
- Asynchronouse electrical signals up to opto boards (5 m)
  - Twinax cable like Pixels
  - LAPA asynchronous LVDS driver on station module (chip reused from MALTA CMOS pixel detector)
  - Sampling rate of 1.28 GHz on lpGBT
    - could still split & delay (1.28→2.56 G) if ToA jitter allows
  - First test over 5 m twinax done at CERN
- Layout to be finalized before services freezing (FDR early 2022)

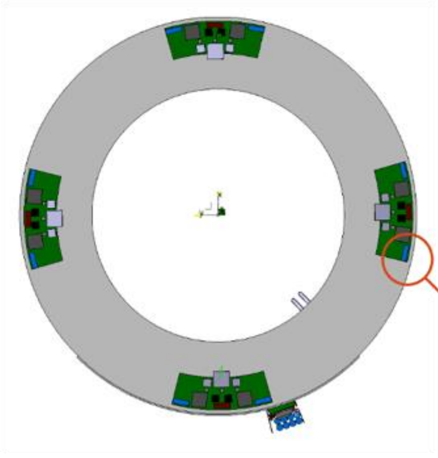
Baseline

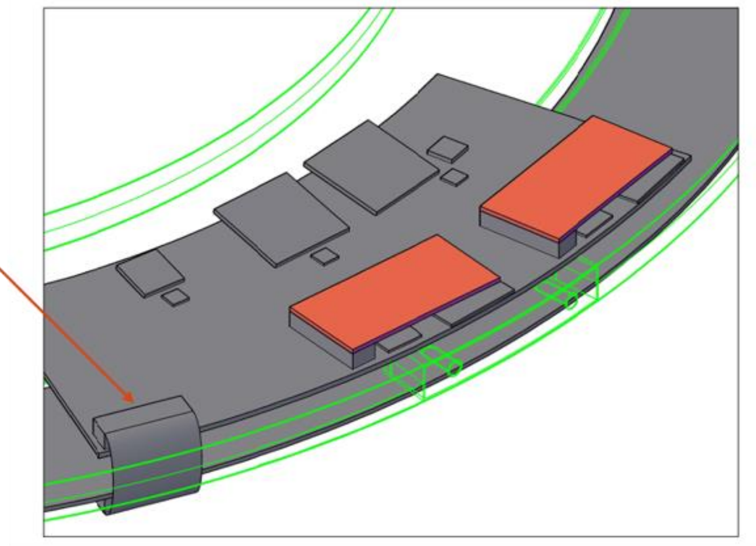


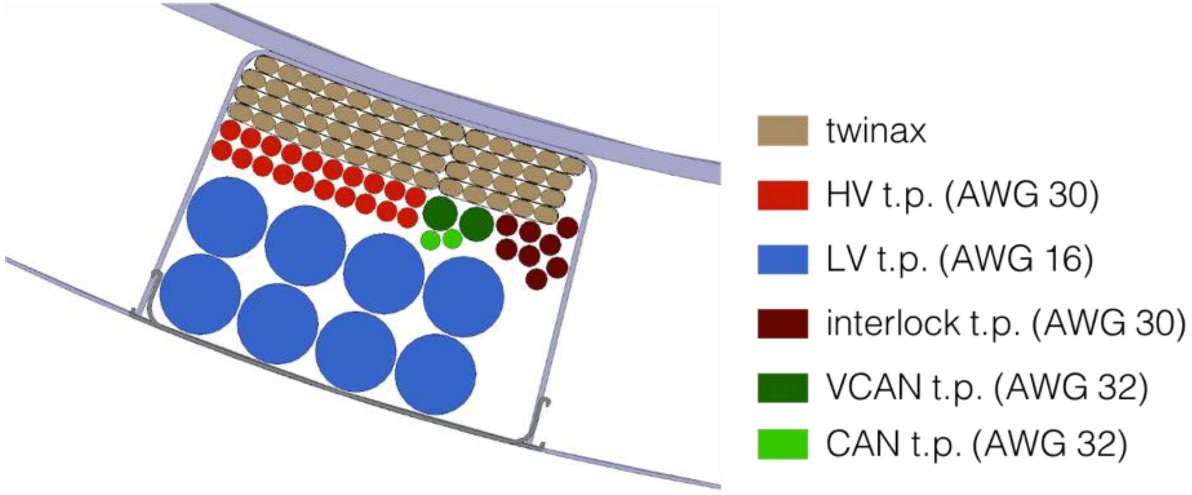


BCM' services

- Stations on dedicated R1 ring within ITk
- Several chips on the station
  - 3 sensors, 3 FE, BLM, DCDC converter, DCS
  - occupies 1/3 of available space on ring
- Thermal load 20 W per ring
  - Cooling required to mitigate radiation damage on ASIC
  - Diamond sensors do not require cooling
- Services occupy approximately 80 % of allocated service channel







	Name	TP/station	TP per side	Voltage	Current
HV	BLM	1	4	500V	<1uA
	3D-diamond(Lumi)	1	4	150V	<1uA
	Planar diamond (Lumi + abort)	2	8	1000V	<1uA
	Silicon	1	4	1000V	<1uA
LV	From bPOL12V	2	8	11V	3A
MOPS VCAN	Nominal 2 (but may be 4 if the capacity is available)		2 (4?)	2V	35mA
TiLock		2	8		
CAN	Nominal 2 (but may be 4 if the capacity is available)		2(4?)	50V	350mA
Twinax	Uplinks		48		
	downlinks		8		

Summary

- BCM' system will be installed in ATLAS ITk pixel end cap for fast beam protection and luminosity measurement
- The system includes:
    - pCVD diamond sensors
    - Fast radiation hard front end ASIC
    - LHC machine-style BLM (slow integrating)
    - lpGBT + FELIX based readout chain – baseline changed
- Different tests demonstrated functionality of the system: lab tests, SEE, test beam
- Several reviews passed, more to come
    - Sensor FDR/PRR early 2022
    - ASIC FDR & Services PDR in early 2022
    - ASIC PRR early 2023