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

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on behalf of ATLAS ITk BCM' group

Overview

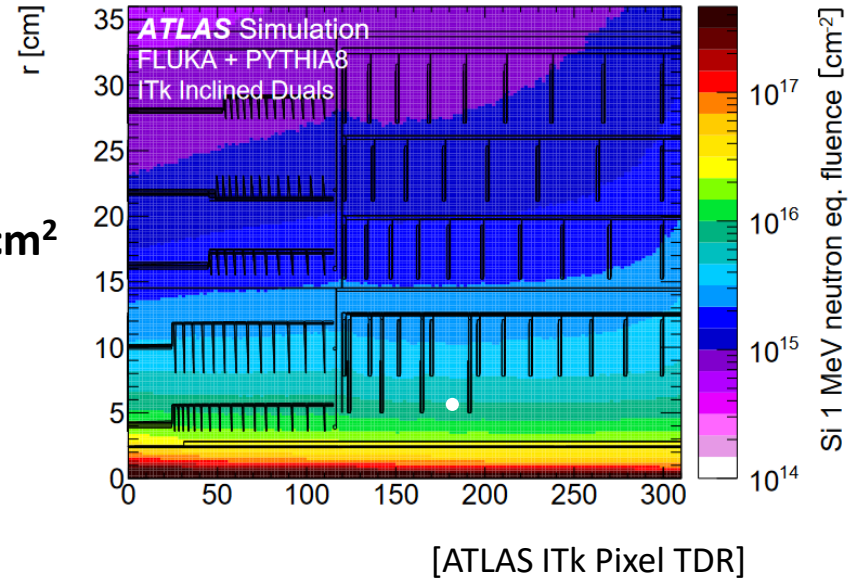
- ATLAS BCM and BCM' Upgrade
- Sensor and front end
- Measurements
- Module and services
- Summary

ATLAS Beam Conditions Monitor

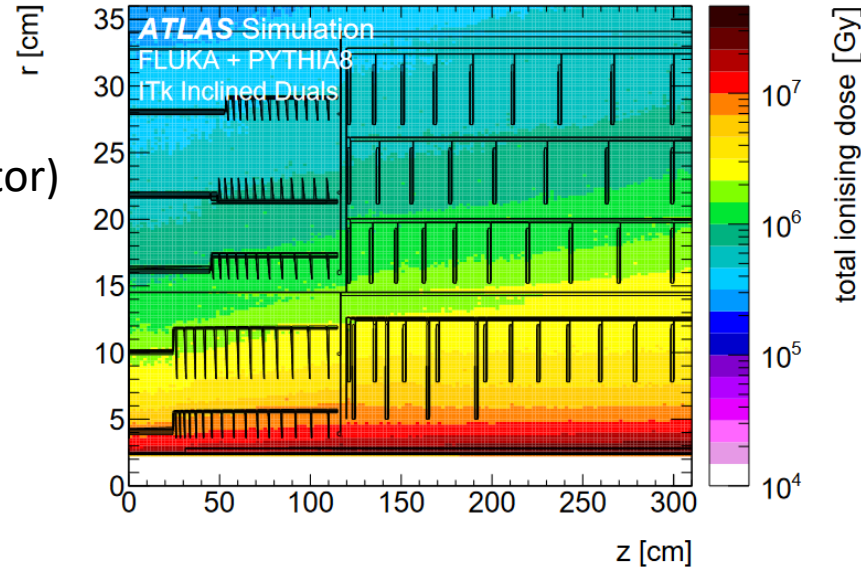
- Beam Conditions Monitor (BCM) in ATLAS at the LHC:
  - Based on radiation tolerant diamond sensors
  - Installed since 2008
  - Located in the Pixel Detector at *z = ± 184* cm, *r = 5.5* cm
    - **NIEL 1 x 10^{15} n_{eq}/cm^2, TID 50 Mrad**, charged particle flux up to **60 MHz/cm²**
- BCM provides 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 almost an order of magnitude
  - Charged particle flux up to **230 MHz/cm²** at pile up **μ = 200**
  - **NIEL 3 x 10^{15} n_{eq}/cm^2**, **TID 300 Mrad** after **2000 fb^{-1}** (including x 1.5 safety factor)



[ATLAS ITk Pixel TDR]

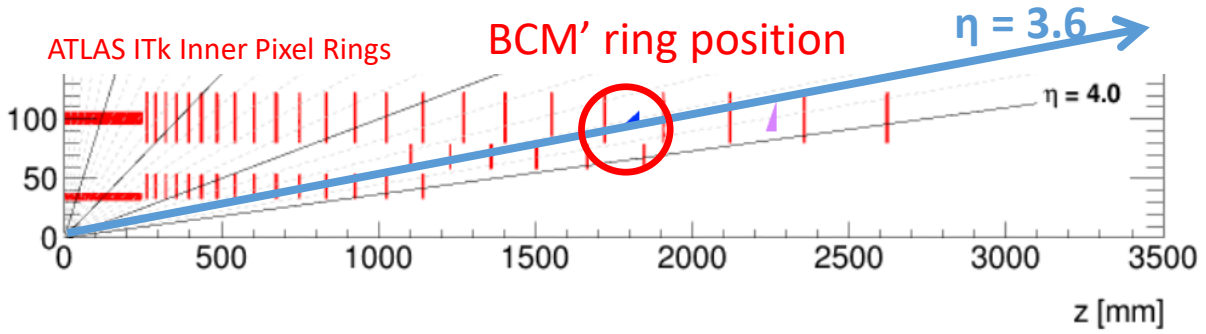


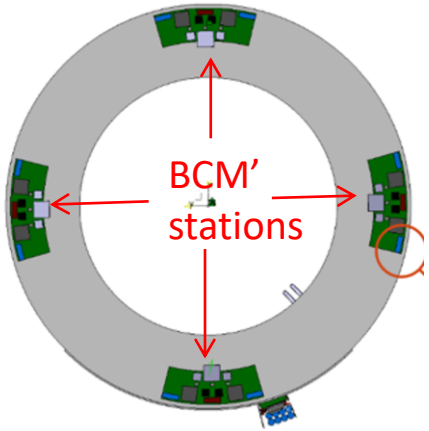
A new **BCM'** system will be installed in ATLAS ITk in 2024
BCM' group: OSU, JSI, Manchester, Wiener Neustadt, CERN

BCM' overview

- Located within the new ATLAS ITk Pixel Inner system on both detector sides at r = 100 mm, *z* = ± 1800 mm (6.25 ns) from Interaction Point
- 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 interval 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) – slow, integrating, electronics copied from LHC machine
  - Luminosity (single MIP sensitivity)

Each with own sensor





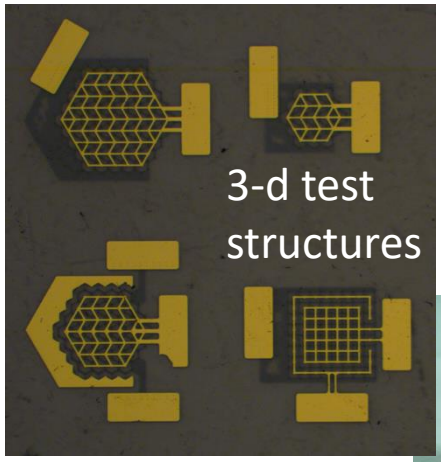
BCM TOF concept

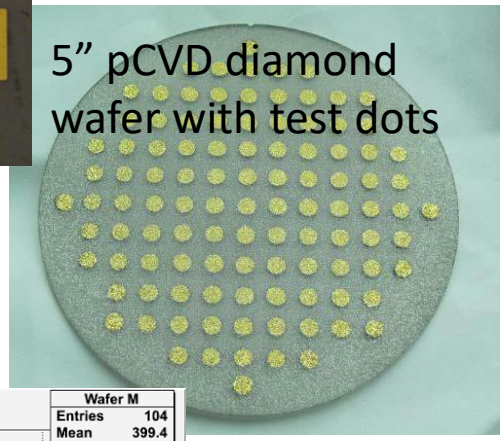
- **Collisions: in time**
- **Background: out of time**

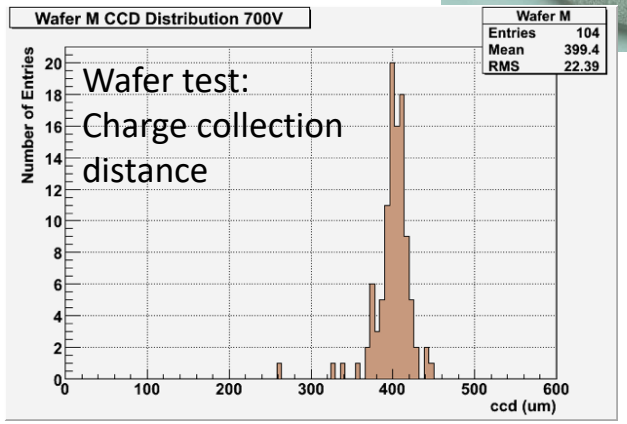
[2008 *JINST 3* P02004]

BCM' sensors

- Sensitivity on very broad range of particle fluxes required
  - Four orders of magnitude, $\mu_{vdM} = 0.01 \rightarrow \mu_{ultimate} = 200$
  - 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:
  - **5 mm x 5 mm** (abort), four pads
  - **10 mm x 10 mm** (lumi), three pads (size 1 mm^2 – 50 mm^2)
  - **1 mm x 1 mm 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 mm^2, 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
- Preproduction will start in mid-2022







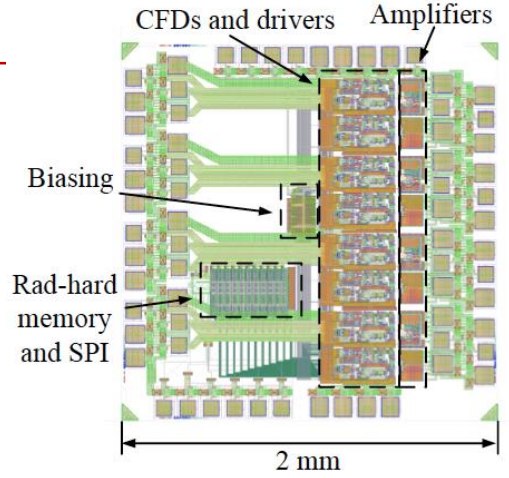
BCM' Front End - Calypso

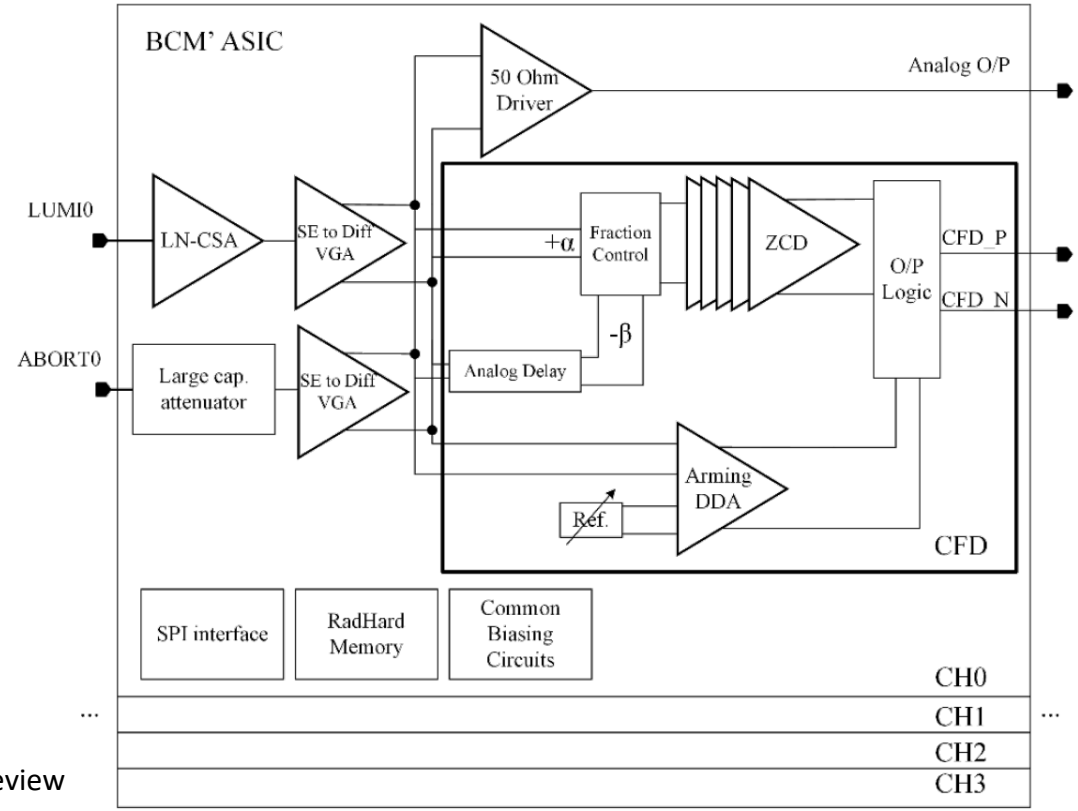
- Calypso: New custom 4-channel front end ASIC
  - TSMC 65 nm process, Multi Project Wafer (MPW), size 2 mm x 2 mm
  - Two (mutually exclusive) input options per channel: *lumi/abort*

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

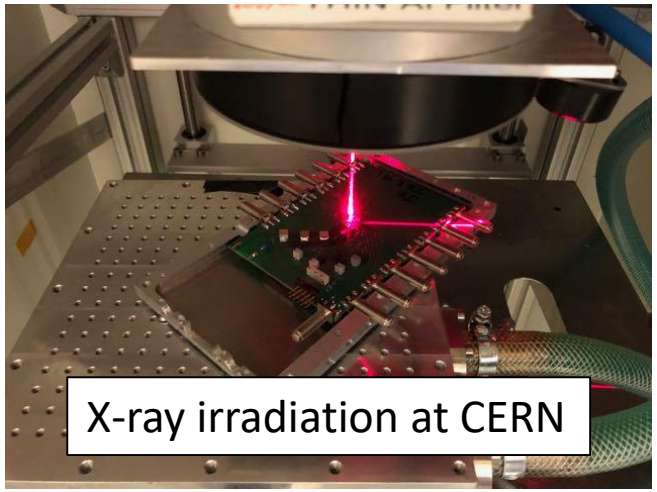


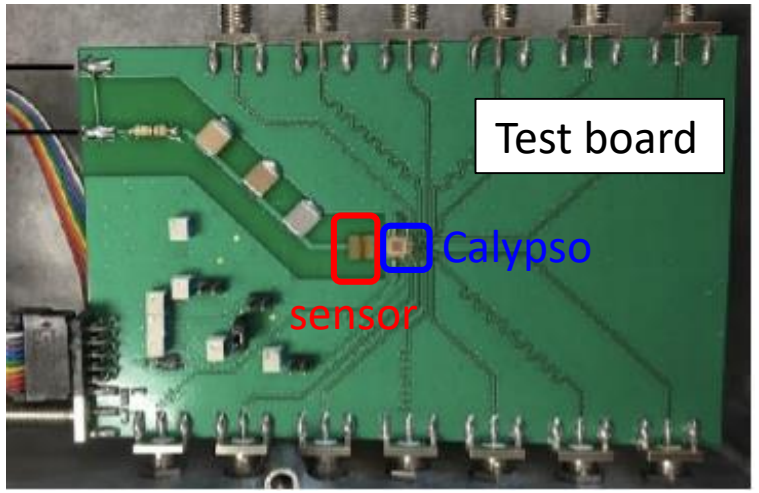


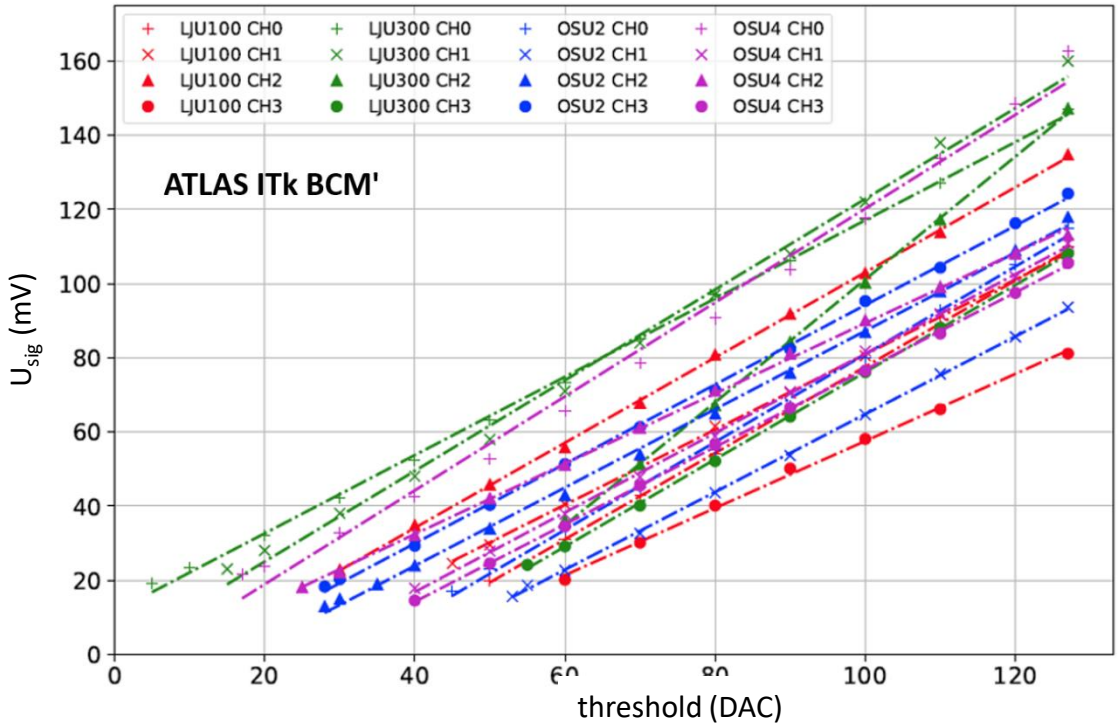
FDR ... Final Design Review
PRR ... Production Readiness Review

Calypso_C Bench Tests

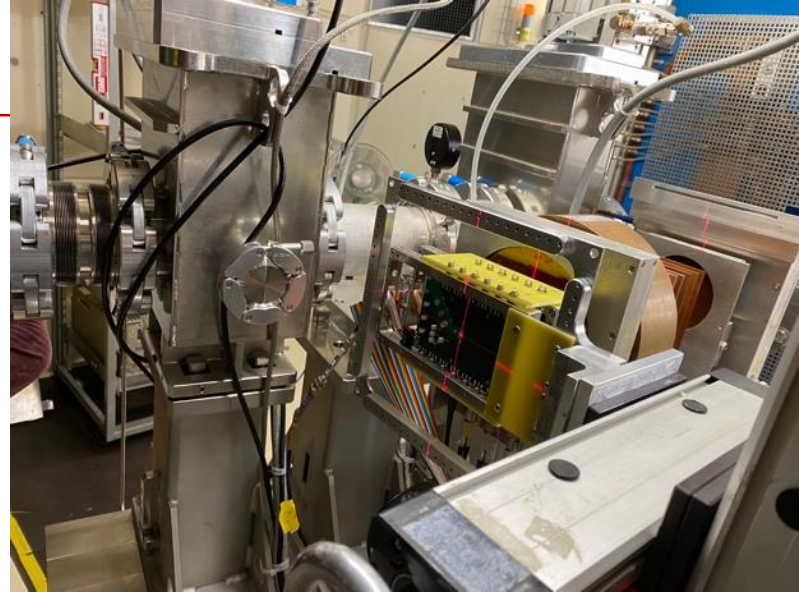
- Single chip test boards assembled at OSU and JSI
- Basic functionality test ok
  - Except (much) larger threshold offset spread than expected from simulation
  - Consistent results at OSU and JSI
- Chips irradiated up to 300 Mrad X-ray (unpowered)
  - Functional after 300 Mrad
  - < 20 % of variation on analog parameters observed
  - Need to irradiate powered and cold (counter-effects!)
- I^2C for chip configuration fully tested







Single Event Effects test at PSI with Calypso_C



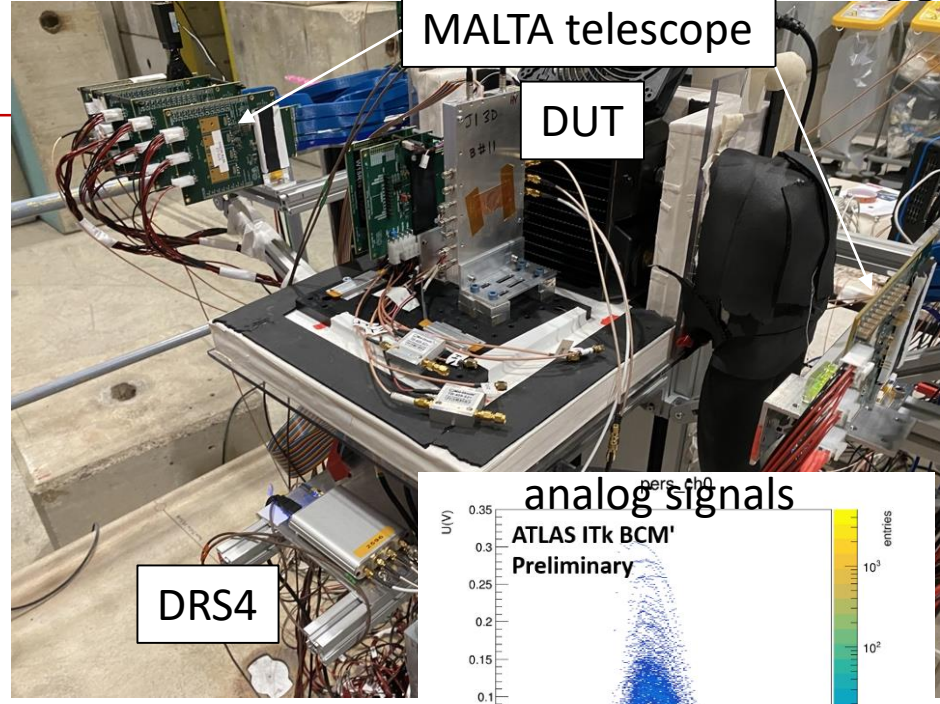
- Aug and Oct 2021, PIF at PSI, 230 MeV protons (3.5e13 p/cm^2 total)
  - **Unirradiated** Calypso_C and Calypso_C irradiated with **300 Mrad** (X-ray)
- Test procedure:
  - Triple Modular Redundancy (TMR) register cells with active feedback
  - 30 8-bit registers i.e. 240 bits loaded with a binary pattern, read out every 10 s
  - If change observed reload and re-start reading
- Results:
  - 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

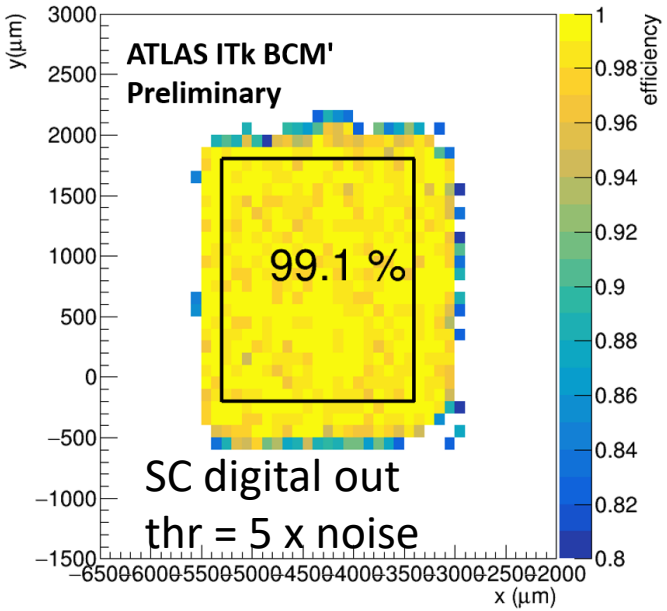
    1111 11**1**1 → 1111 11**0**1
    0**01**0 1100 → 0**10**0 1100
    - TMR logic probably at edge of functionality

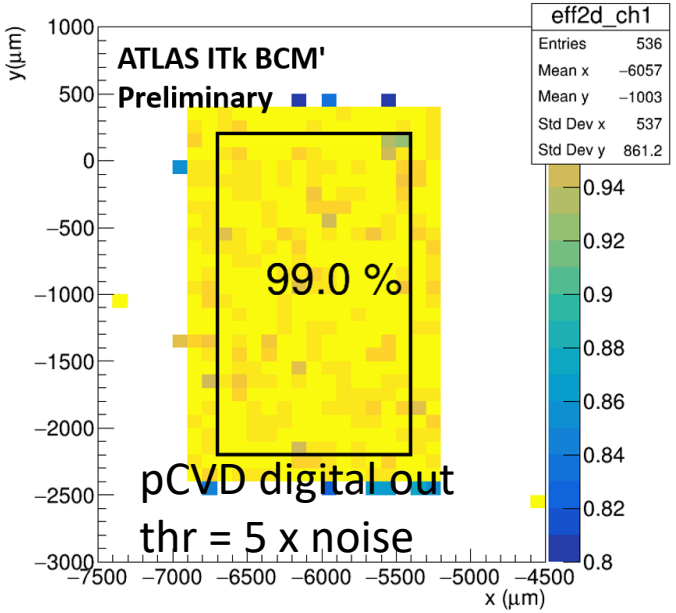
- **Not problematic for operation, since registers can be written at will**

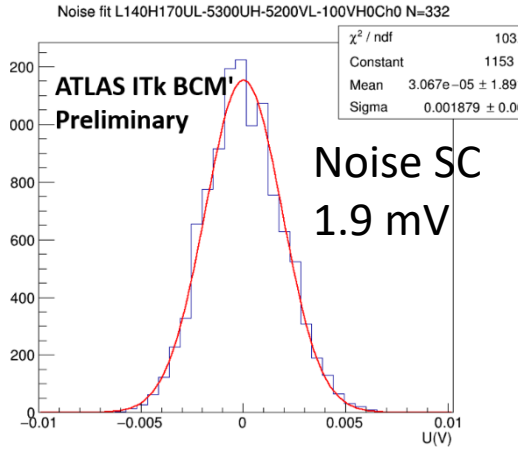
Test beam at CERN SPS

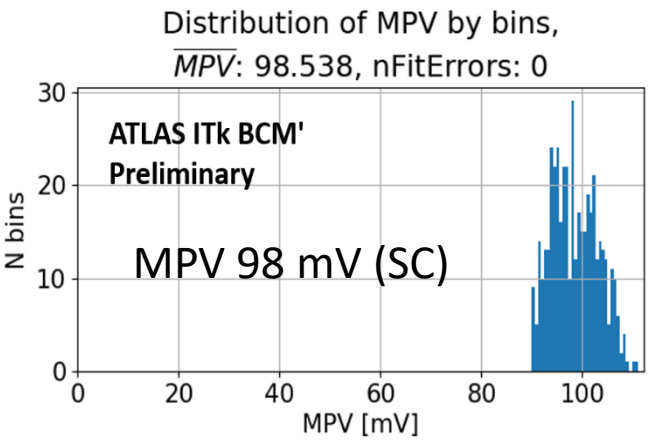
- Test beam with 120 GeV pions, MALTA CMOS telescope
- Oct and Nov 2021 with refurbished diamond sensors
- Single crystal and pCVD diamond samples (unirradiated)
- Read out analog and digital signals with DRS4 oscilloscope
- Efficiency above 99 % with digital signals in both samples
  - Analysis still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











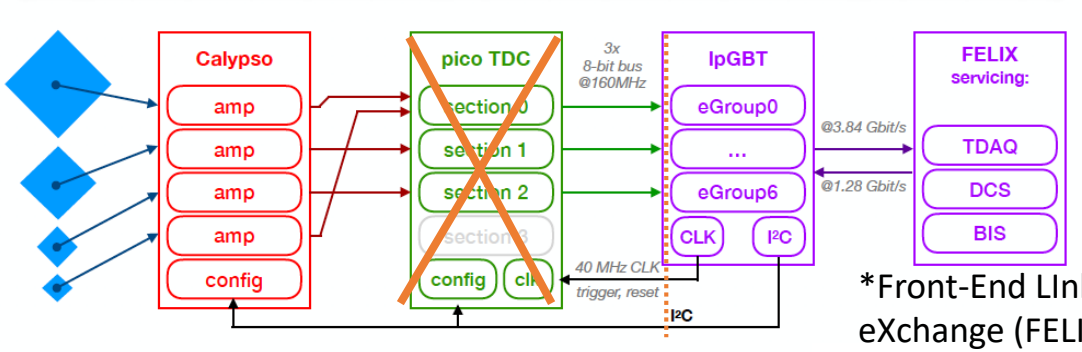
BCM' readout

- Original baseline was

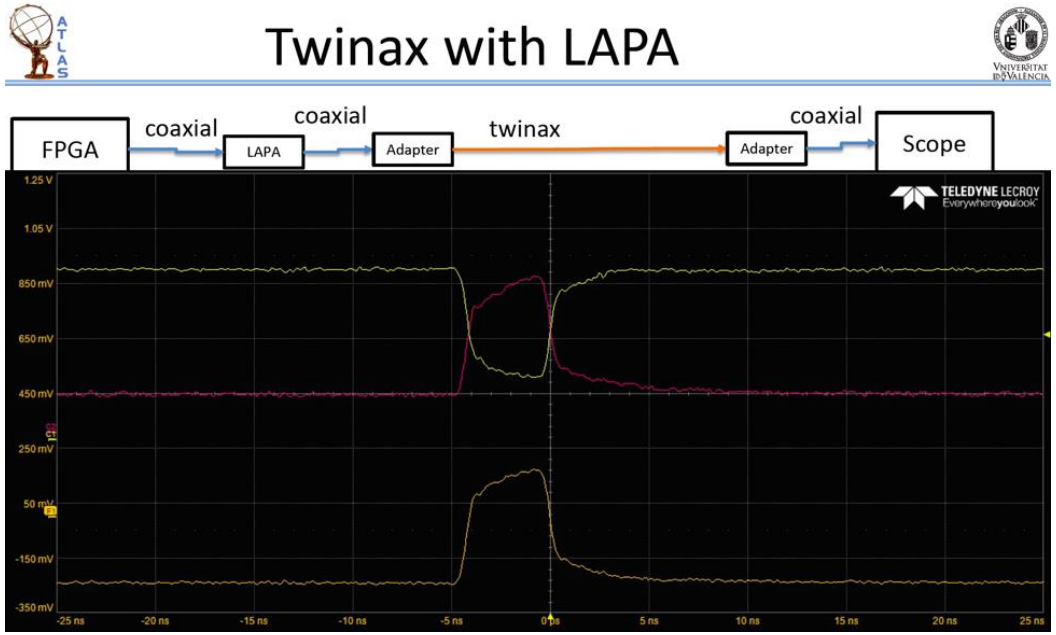
  Calypso → picoTDC (digitization) → lpGBT (to optical) → FELIX*

  - Use of picoTDC abandoned due to delivery, radiation issues
  - lpGBT on opto-panel (lower radiation environment)
- Asynchronous electrical signals up to opto boards (5 m)
  - Twinax cable like ITk Pixel
  - LAPA asynchronous LVDS driver on station module (chip reused from MALTA CMOS pixel detector project)
    - First test over 5 m twinax done at CERN
  - Sampling rate of 1.28 GHz on lpGBT
    - To be tested
- Layout to be finalized before services freezing (early 2022)

Baseline

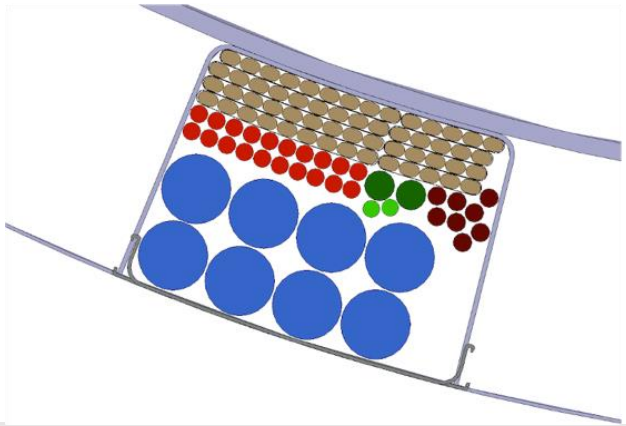


*Front-End LInk eXchange (FELIX)

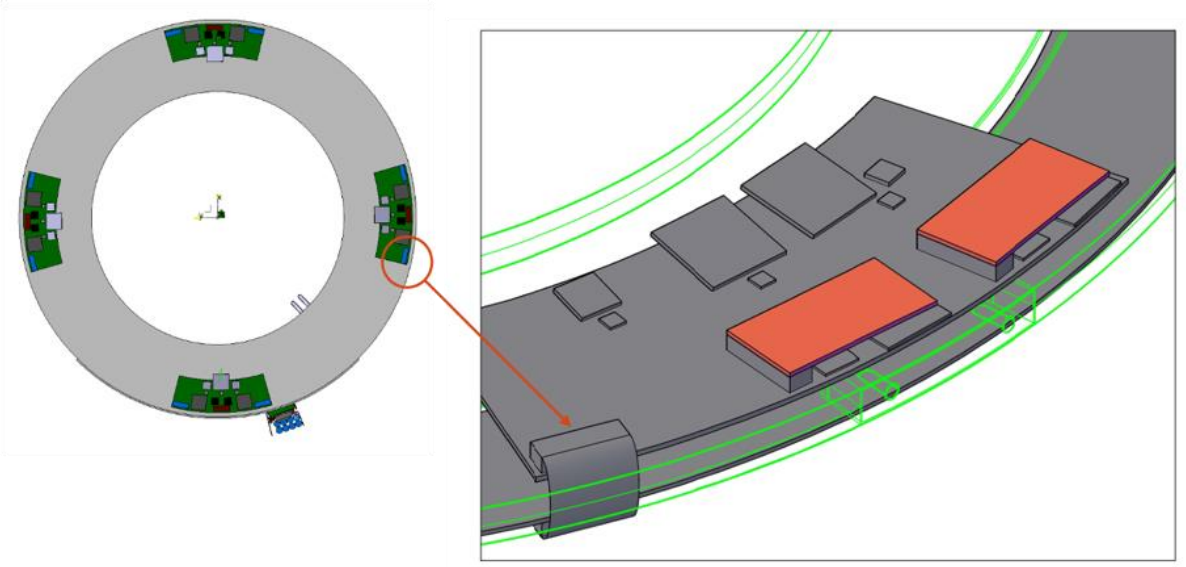


BCM' services

- Four stations on dedicated R1 ring within ITk Pixel Inner System
  - Occupying 1/3 of available space on ring
- Several chips on the station
  - 3 diamond + 1 Si sensor, 3 FE (1 abort, 2 lumi), BLM, 2 LAPA, DCDC converter, DCS
- Thermal load 20 W per ring
  - Diamond sensors do not require cooling, but cooling required to mitigate radiation damage on ASIC
- Services occupy approximately 80 % of allocated service channel routing services from the rings to the tracker edges



twinax
HV t.p. (AWG 30)
LV t.p. (AWG 16)
interlock t.p. (AWG 30)
VCAN t.p. (AWG 32)
CAN t.p. (AWG 32)



	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 Inner system 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, moving to preproduction/production in 2022