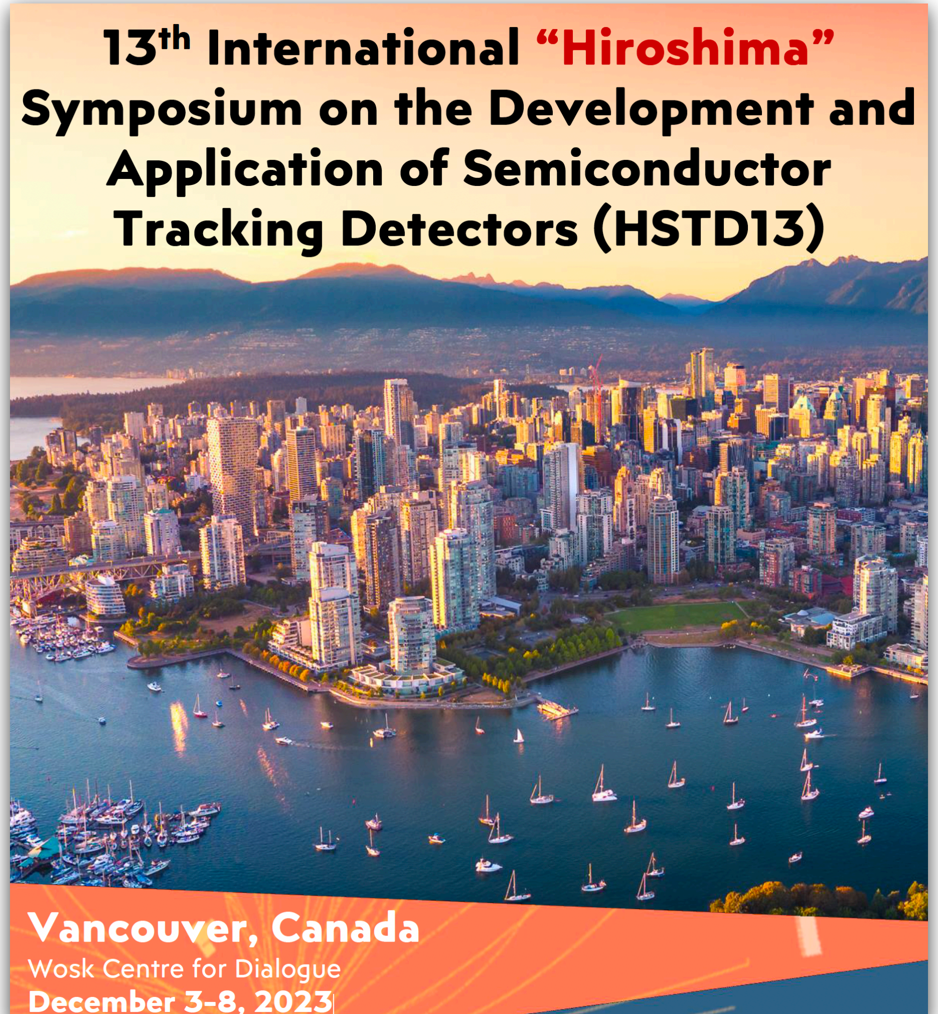

ATLAS EXPERIMENT

& RD42

Development of **the BCM' system** for beam abort and luminosity monitoring in ATLAS based on a segmented polycrystalline CVD diamond sensor and dedicated front-end ASIC

A. Gorišek on behalf of **ATLAS BCM'** and **RD42** collaborations

6 December 2023

Jožef Stefan Institute, Ljubljana, Slovenia

Motivation

- ★ In ATLAS the current BCM detector is installed and working reliably
  - ★ In LHC Run 1 it served as the primary ATLAS online luminosity monitor
  - ★ In Run 2 and 3 it is the primary safety system with ability to dump LHC beams in case of danger to the delicate parts of Inner Detector

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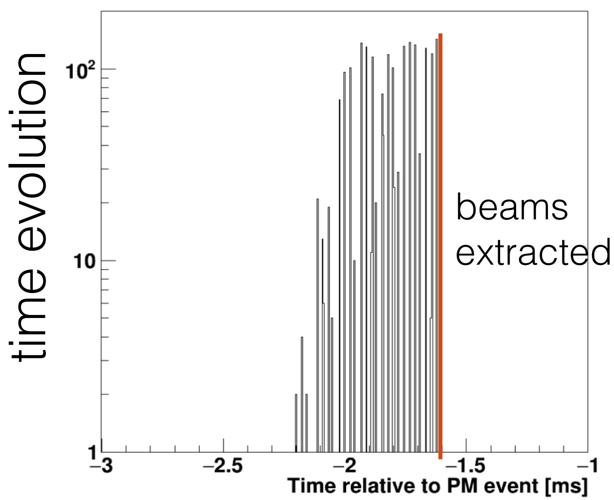
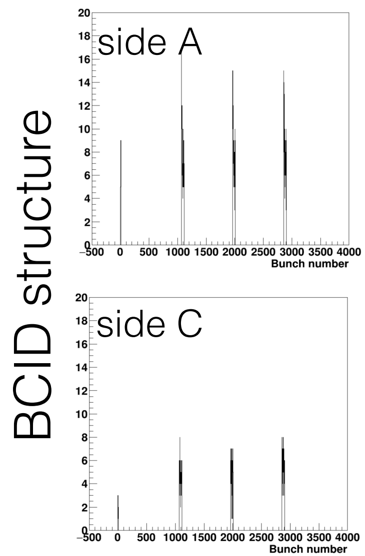


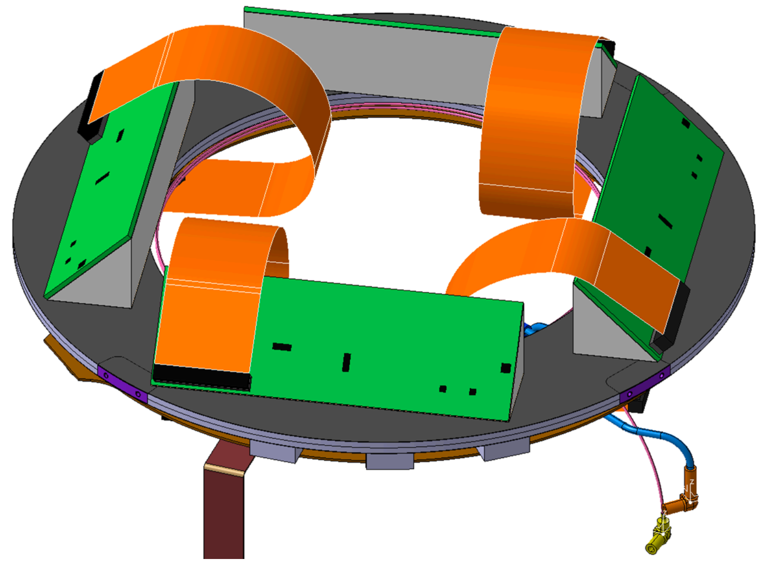


- ★ BCID structure shows more activity on A side than on C side which usually is the case for “events” coming from C to A
- ★ ~500 us to extract the beams — typical

- ★ We are developing an improved system also based on pCVD diamond sensors and a novel dedicated Front-End ASIC in radiation hard 65nm technology — conveniently called **ATLAS BCM'**

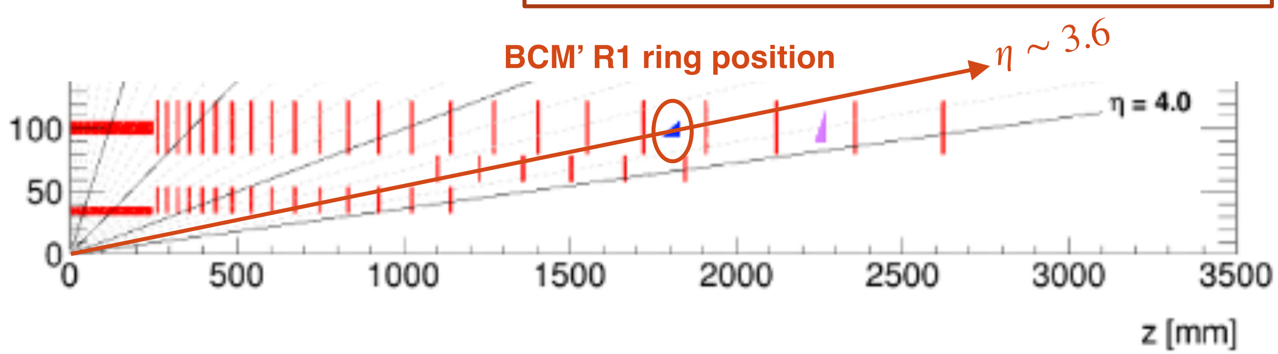
The concept

- ★ Provides bunch-by-bunch measurement (→ asynchronous detection) of:
  - ★ Fast safety system for ATLAS (>10^5 MIP)
  - ★ Luminosity measurement (MIP)
  - ★ Background monitoring (MIP)
- ★ Separate background from collisions with TOF
  - ★ Excellent time resolution
  - ★ Keep position close to optimal spot at $z \sim 1875$ $(6.25\ \mathrm{ns})$
    → "L1 Pixel ring" at $z \sim 1800\ \mathrm{mm}$
- ★ 4 modules per side
  - ★ with abort (multi-MIP), lumi (single-MIP) BCM'
  - ★ at $\varphi = 0°, 90°, 180°$ and $270°$ for luminosity measurement



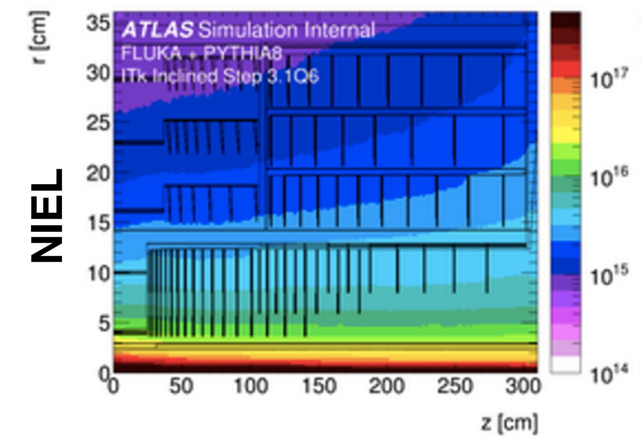
- ❖ Plan to use tracks from ITk to calibrate the detector and monitor its long-term stability

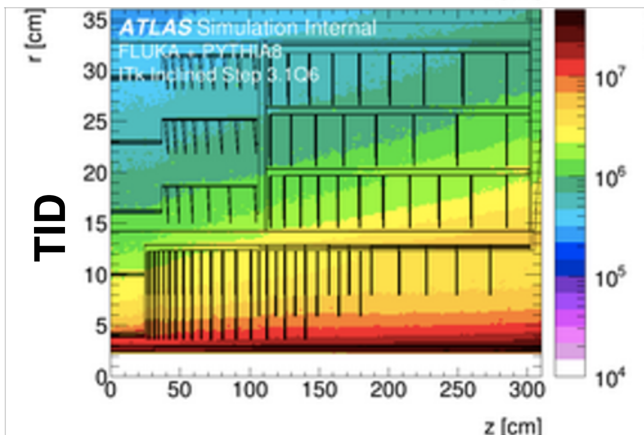
- ★ +BLM (redundancy)
  - ★ slow, integration time: $40\ \mu s$
  - ★ on the other side of the ring



The ATLAS BCM’ environment

- ★ ATLAS radiation simulation, r=9-12 cm, z=1.8 m
- ★ NIEL&TID for 2/ab, nominal → **3/ab** (**x1.5** safety factor)
  - ★ TID ≲ 200 Mrad → **300 Mrad** (more for services @PP1)
  - ★ NIEL ~ 2×10^{15} n_{eq}/cm^2 → **3×10^{15} n_{eq}/cm^2**
    - ★ low neutron fraction
    - ★ n_{eq} for diamond? → take 3×10^{15} 800 MeV p/cm^2 for sensor benchmark
- ★ Charged particle flux at r=10 cm
  - ★ per bunch crossing ~0.032/cm^2 x μ (50% secondary 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/cm^2 20MeV+ hadrons (SEE)





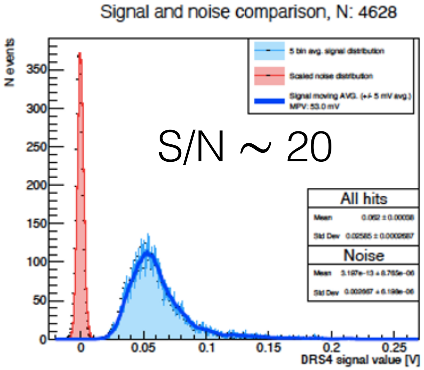
Fluence and dose values for BCM'. Values of 1 MeV fluences and dose are normalised to 2000 fb^{-1}. All other values are per event. **No safety factors have been applied to these values.**

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	1.56	28.6	12.8

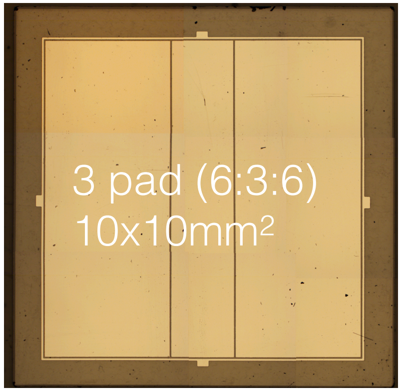
pCVD Diamond sensors

- ★ Focus on pCVD diamond sensors from US vendor (II-VI) from newly grown wafers

- ★ 1x1cm^2 (lumi, 3 pads), 5x5mm^2 (abort, 4 pads), max size ~25 mm^2, min size ~1 mm^2
  - ★ CCD (at 1000 V) is now ~in specs (several iterations of wafer growth needed + surface processing)



- ★ TB data from 5 10x10 sensors from two different wafers (H0, S0 S7, S8, S9) connected to Calypso-C/D ASIC on single chip boards look promising
  - ★ Channel mask for lumi sensors converged to pads of "**6:3:6**" size. 6-pads the largest single pad area (capacitance close to 4pF) that will be connected to a single readout channel
  - ★ S/N ~20 routinely achieved with non irradiated detectors



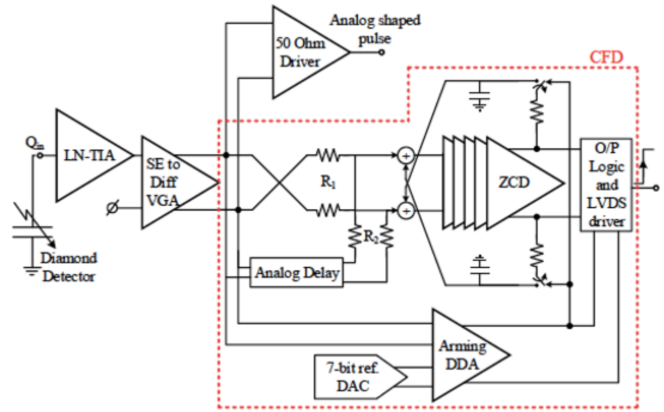
- ★ Single pad sensors (3D-pCVD diamond, Si diode) in addition

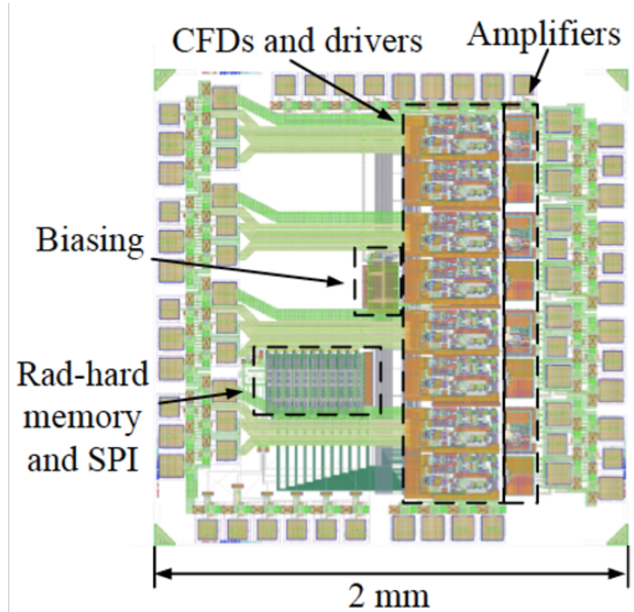
➡ H. Kagan, *Recent Results from Diamond Detectors* on Thursday

FE ASIC — Calypso✤

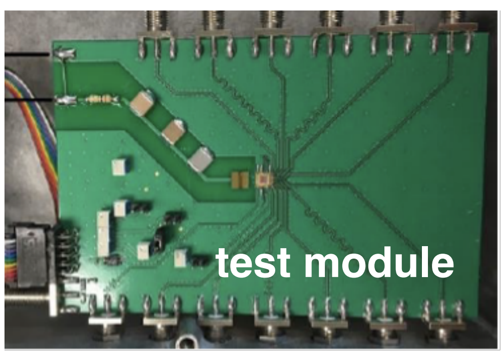
- ★ 4+4 channel FE designed in TSMC 65 nm process (2x2 mm²)
  - ★ MPW submitted through Europractice/IMEC
- ★ 2 types of channel: luminosity and abort
  - ★ optimised for 2-5 pF detector capacitance
  - ★ <1.5 ns peaking, <15 ns settling time @2 pF
  - ★ <100 ps time jitter @2 pF for >3.6 ke signals
  - ★ **luminosity**: (130 + 55 /pF)e noise , ± 50 ke⁻ dynamic range
  - ★ **abort**: ± 750 Me⁻ dynamic range (S/N not an issue)
- ★ 4th iteration Calypso_D submitted in Oct ’22, received in spring 2023, needed to be FIBed. Fixed version submitted in Aug ’23, just received.

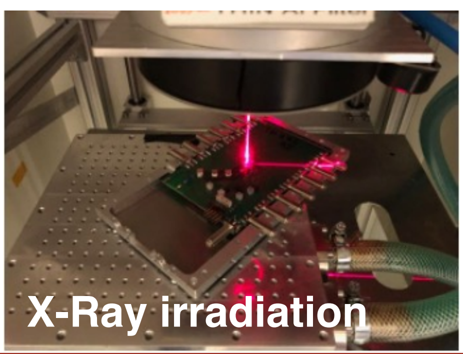
DOI: 10.1109/TNS.2023.3283220





Calypso_B

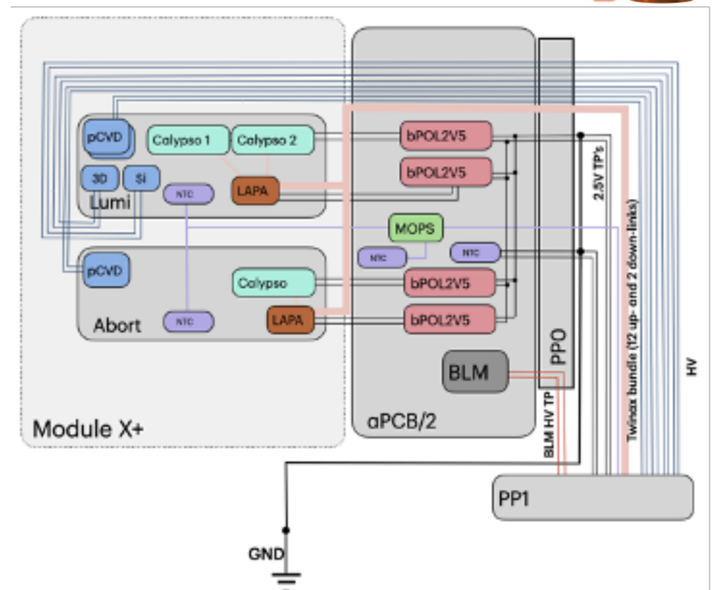


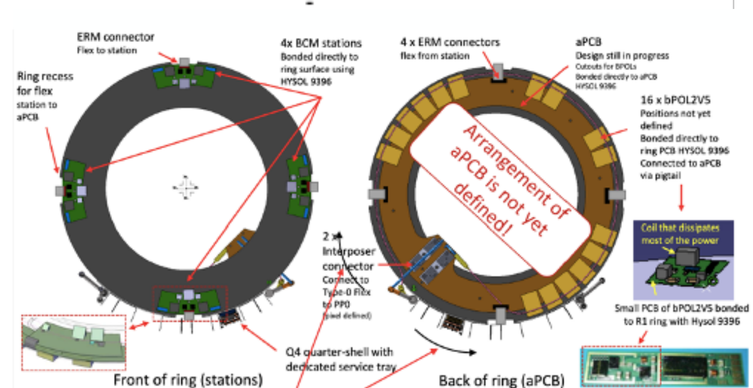


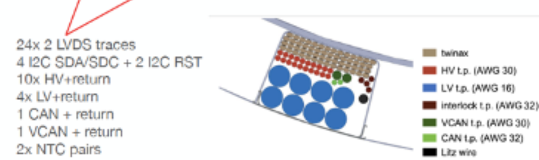
✤Daughter of Atlas

System overview

- ★ **BCM’** is a part of the **ATLAS ITk**, and by itself a fully featured system
  - ★ LV, HV, Data, Command, DCS, Interlock, Cooling
  - ➡ Very complex and distributed services
- ★ Services baseline follows ITk Pixel Inner System wherever possible (important differences!):
  - ★ LV with DC-DC (bPOL) — different to Pixel
    - ★ 1st stage in opto-box, 2nd on aPCB
  - ★ HV up to 1000 V (ITk Pixel 750 V)
  - ★ DCS, Interlock, Cooling, PP3 ~ Pixel
  - ★ PS, PP2, PP1, PP0 ~ Pixel with minor modifications
  - ★ aPCB and modules on the carbon fibre ring – BCM’ specific
- ★ Complex grounding and shielding will follow the ATLAS guidelines and recommendations.

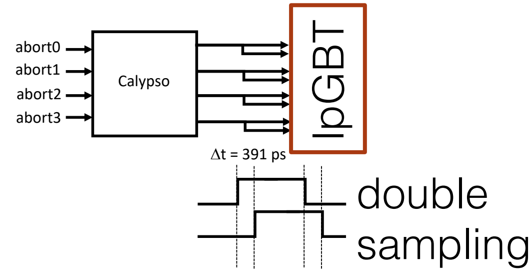




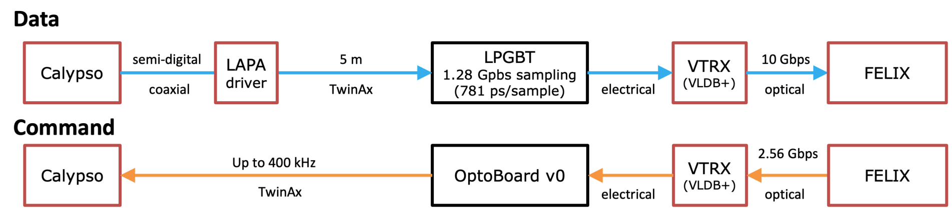


Readout/system test setup

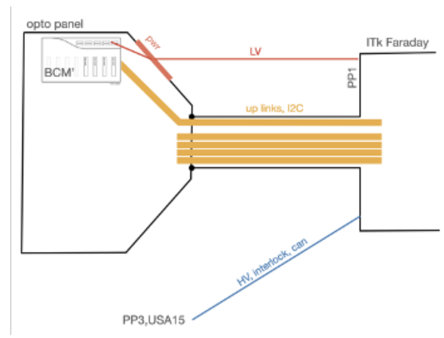
- ★ Baseline BCM’ readout:
  - ★ Calypso digital outputs are driven by LAPA driver (LVDS level signals — PoS(TWEPP-17)038)
  - ★ 5m "Twinax" t.p. cable (like Pixel)
  - ★ Signal into lpGBT, digitise @1.28 Gbs
    - ★ could still split & delay for 2.56 Gbs
  - ★ ToA and ToT reconstructed in FELIX



- ★ Full chain up to FELIX test @CERN
  - ★ Bi-directional (data, command)
  - ★ Develop into a system test set-up

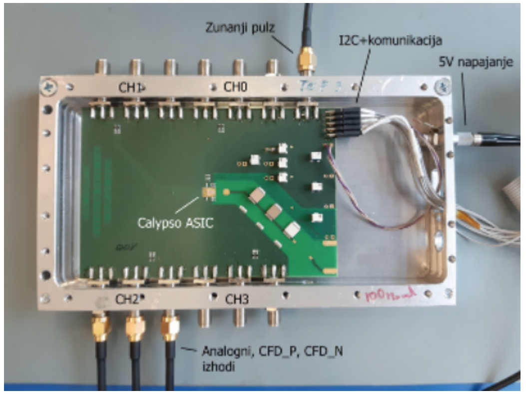


- ★ BCM’ opto readout
  - ★ Single opto-box in pixel panel
    - ★ minimal configuration compatible with @1.28 Gbs



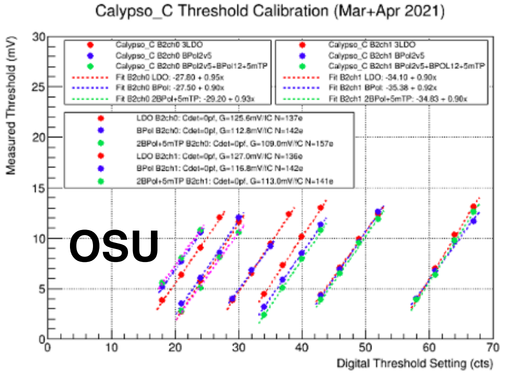
Measurements with prototype modules

★ Single chip test boards routinely assembled at OSU, Columbus and JSI, Ljubljana



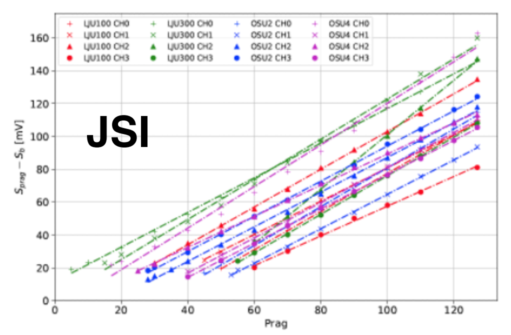
★ Basic functionality test ok

- ★ larger threshold offset spread than expected from simulation — addressed in Calypso_D ✓
- ★ consistent results at OSU and JSI ✓



★ Bare chips (Calypso_C) irradiated up to 300 Mrad X-ray

- ★ chip works after 300 Mrad
- ★ <20 % of variation on analogue parameters observed
- ➡ need to irradiate powered and cold (counter-effects!)
- ➡ need to test before and after irradiation

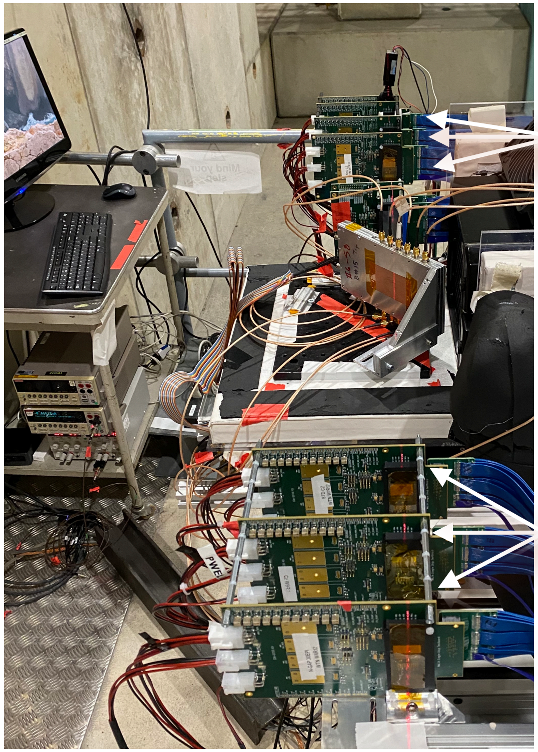


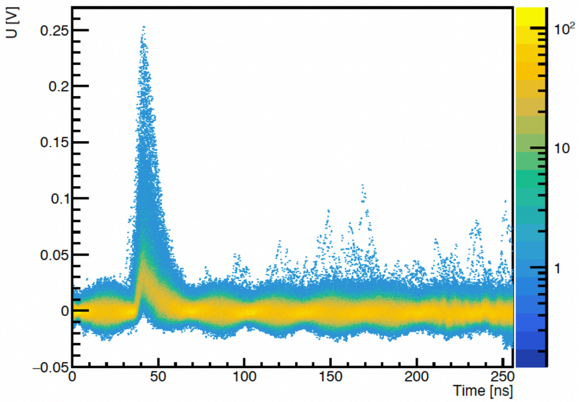
★ I2C configuration fully tested

- ★ Triple Modular Redundant memory for all 240 registers

Beam test results @ SPS H6

- Used **MALTA** monolithic pixel detector based on TowerJazz 180 nm CMOS technology developed at CERN for beam **telescope** (doi.org/10.48550/arXiv.2304.01104)
  - 2x2 cm^2 active area
  - 512x512 pixels of 36.4 μm pitch
  - 6 planes
  - *Tracking cuts*: nTracks, SlopeX, SlopeY, Chi2, track within the fiducial area, loose timing cut…
- Data from multiple devices collected in multiple test beam campaigns throughout the 2022/23

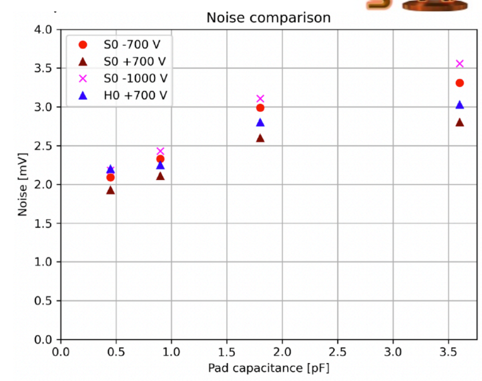




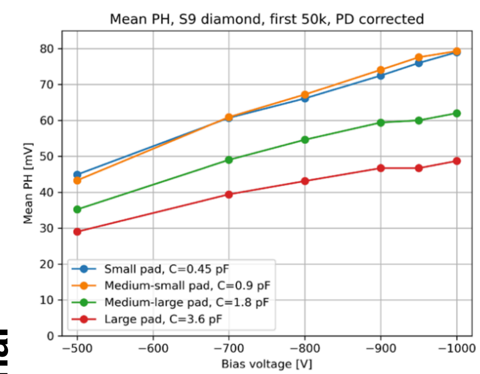
Beam test results @ SPS H6

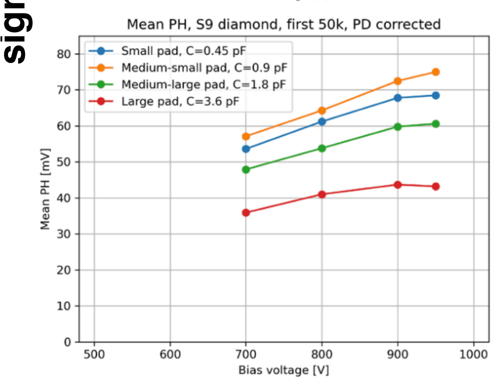
- ★ Noise measured depends on input capacitance as predicted
    - ★ Capacitance larger than simplistic geometric model (~ +1 pF)
- ★ Difficult ramp-up to nominal voltages (+/-1000 V) due to increase in leakage currents (not seen in bare sensors)
    - ★ RIE/ICP surface processing reduces this issue dramatically
- ★ Mean Calypso gain decreases with input capacitance at the upper design limit of few pF
- ★ Signals large enough to have a working range for choice of the threshold.

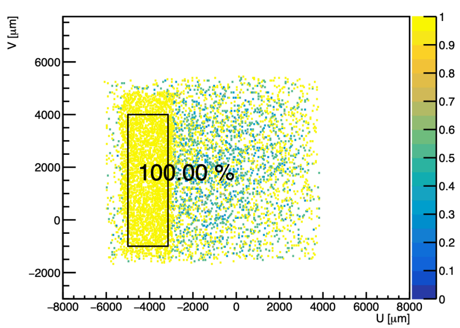
noise

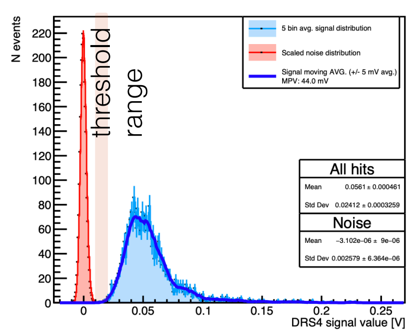


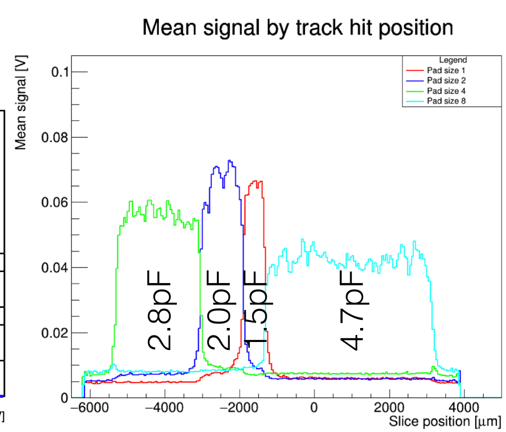
signal





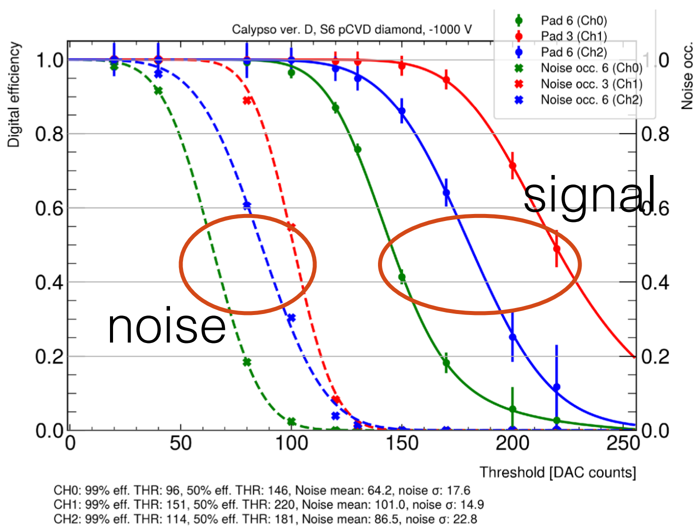


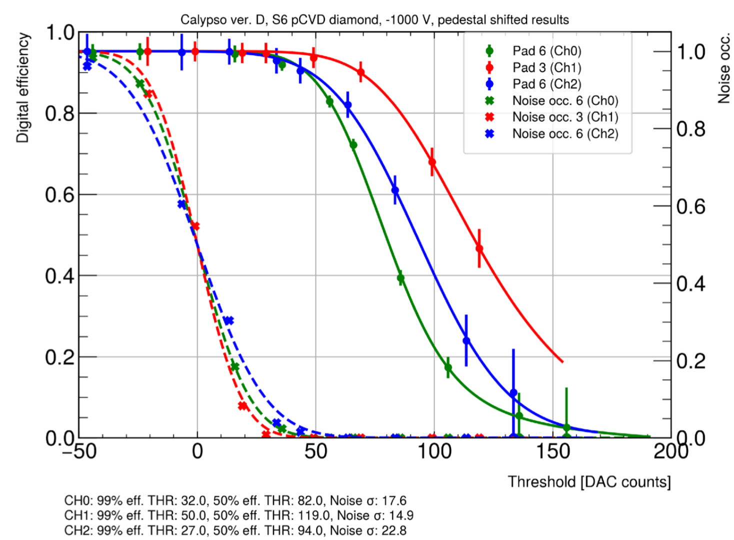




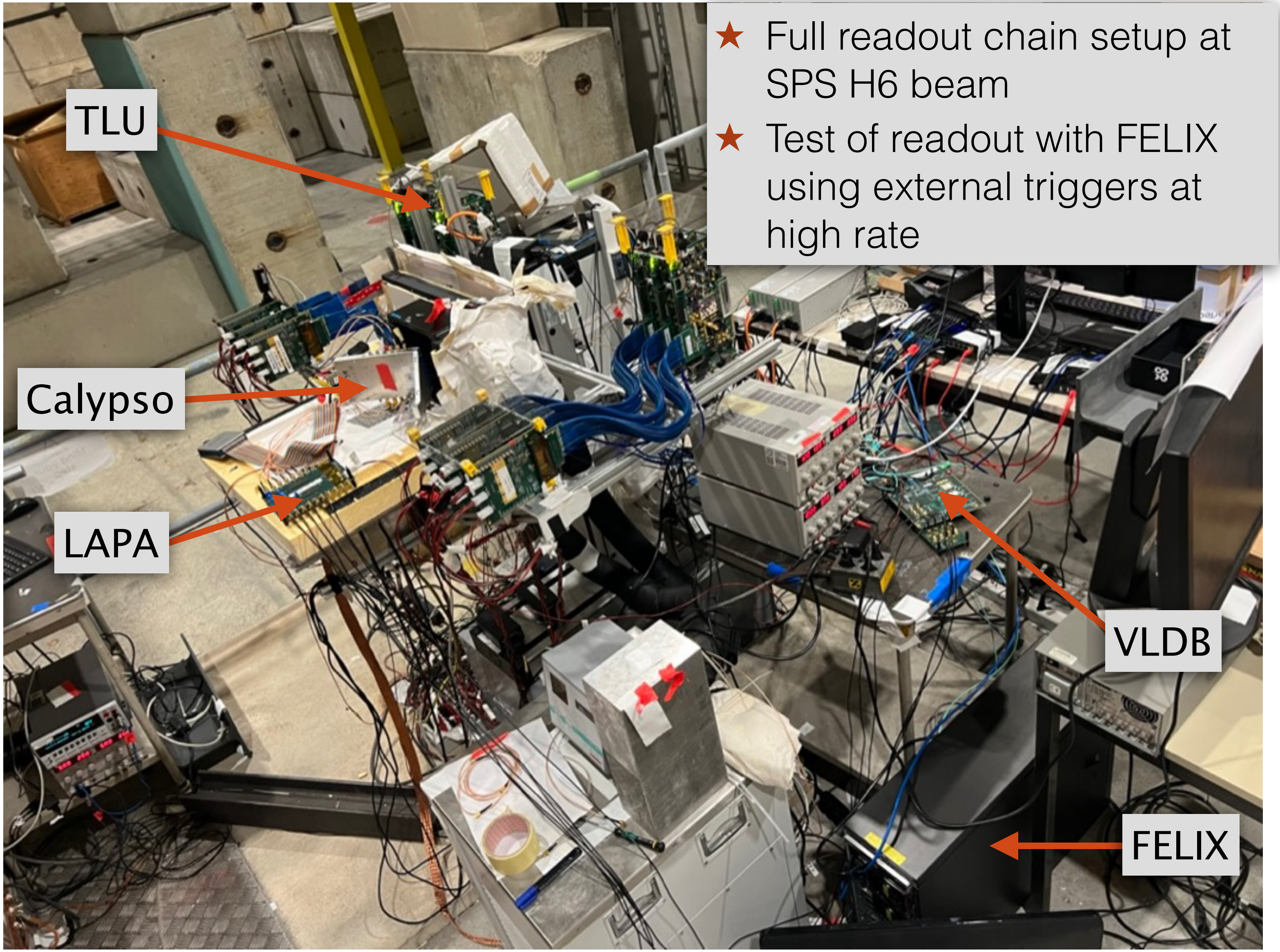
Beam test results @ SPS H6

- In 2023 Calypso_D modules were tested with the final 3-pad geometry
  - Recorded digital signals only with analog output drivers switched off
    - Final configuration — realistic conditions
  - Threshold channel to channel spread can be mitigated with threshold offset DAC
  - Example of noise and signal threshold scans are shown below
    - Clear separation / operating point





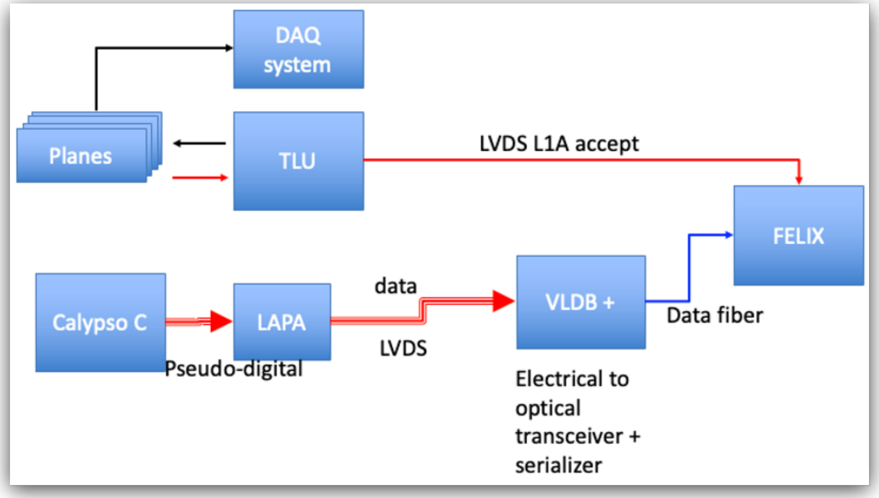
System test @CERN H6 testbeam

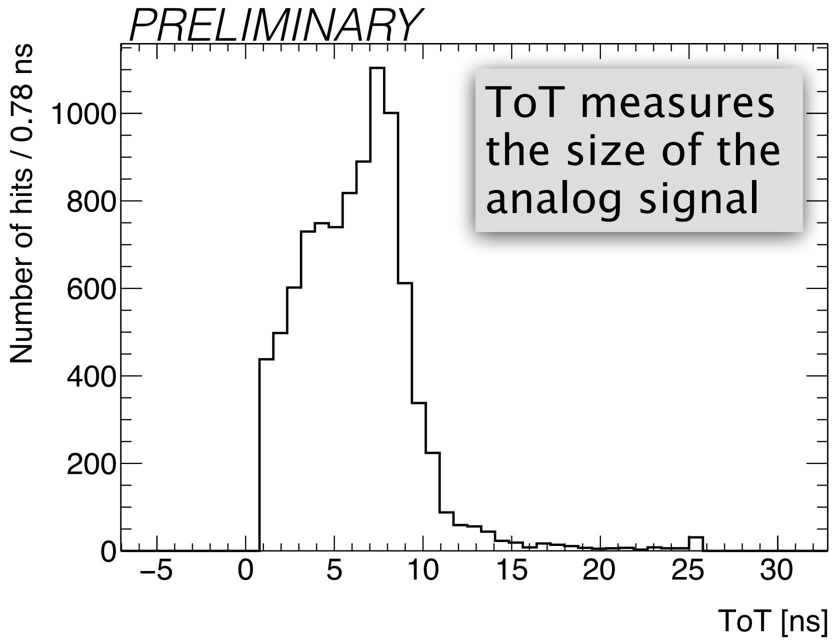


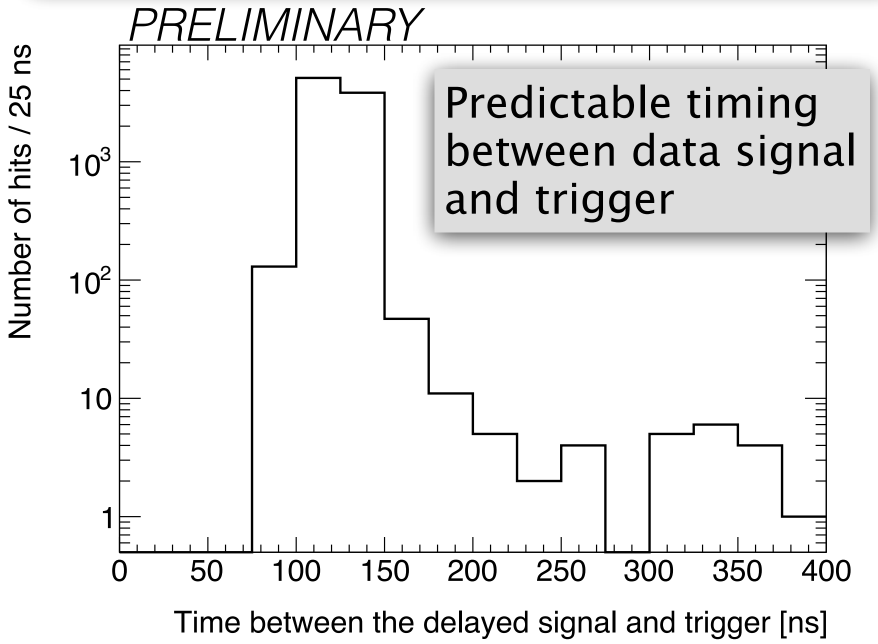
- Full readout chain setup at SPS H6 beam
- Test of readout with FELIX using external triggers at high rate

System test @testbeam

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



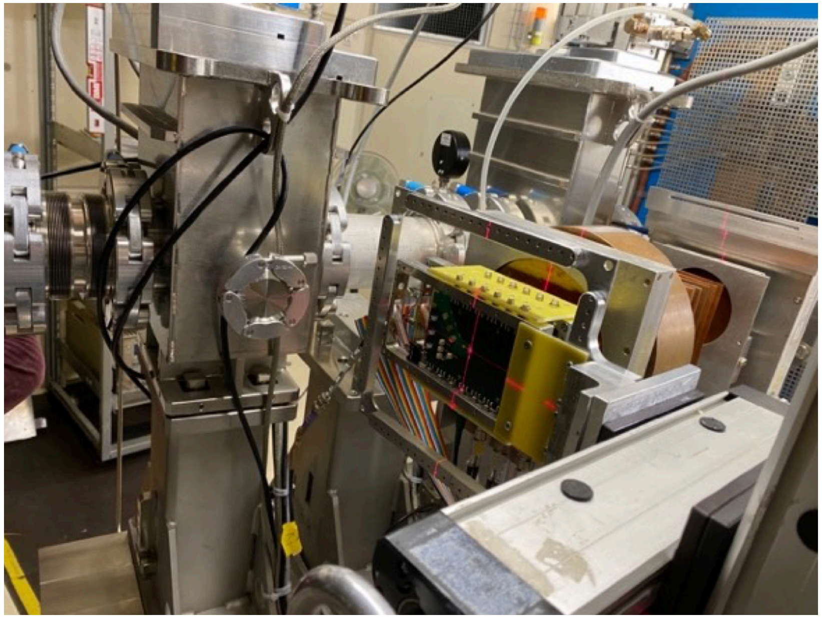




Single Event Effect test at PSI

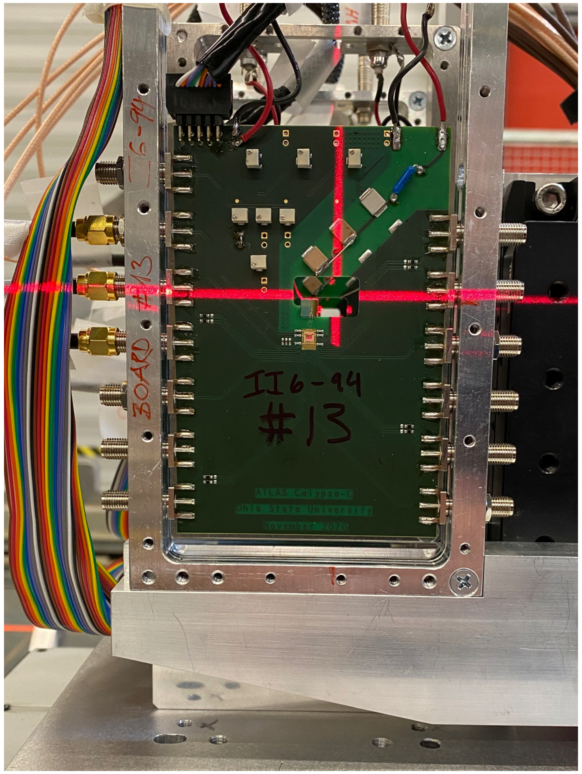
- Test at PIF @PSI (Oct 2021), 230 MeV protons (3.5 10^{13} p/cm^2 total)
  - Unirradiated Calypso_C and Calypso_C irradiated passively to 300 Mrad
- Test procedure:
  - 240 bits loaded to Triple Modular Redundancy (TMR) registers, read out every 10 s
  - If change observed (after 2 reads) reload and re-start reading
- Events observed:
  - **No events** observed with **unirradiated chip**
  - consistent with ITk Pixel (65nm) upper limit 10^{-14} cm^{-2}
  - **Two events** observed in **irradiated chip** (300 Mrad)

1111 1111 → 1111 1101
0010 1100 → 0100 1100

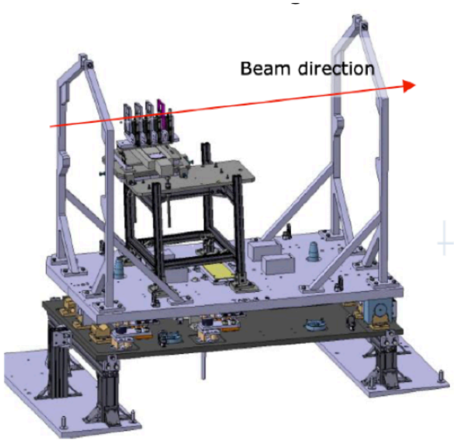


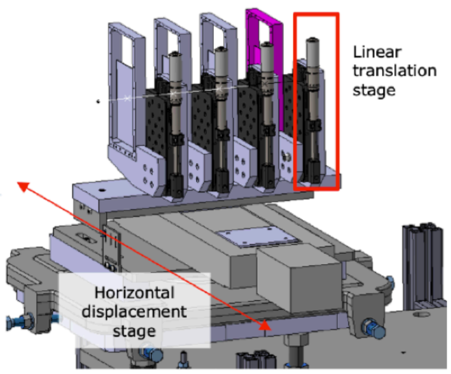
HiRadMat @ CERN

- ★ Plan to put simultaneous bunched beam (halo/scattered particles) trough BCM' sensors
  - ★ To fully test the abort functionality (simultaneous MIPs)
  - ★ To test "train effect" of 25 ns bunched MIPs for luminosity measurement systematics estimate



- ★ Extraction of full SPS beam (up to 288 nominal bunches to a beam dump
- ★ Experiment positioned in front of the beam dump
- ★ FE did not withstand the induced signal from the beam during the first tests in 2022— will modify (adding a beam-pipe) and repeat in 2024





Acknowledgements

- The efforts to develop and build the ATLAS BCM’ shared by many people from groups at:
  - J. Stefan Institute, Ljubljana, Slovenia
  - Ohio State University, Ohio, USA
  - CERN, Geneva, Switzerland
  - FH Wiener Neustadt, Austria
  - University of Manchester, UK

Jožef Stefan Institute

CERN

The Ohio State University

FACHHOCHSCHULE WIENER NEUSTADT University of Applied Sciences – Austria

MANCHESTER 1824 The University of Manchester

- With huge help from the ATLAS ITk community:
  - CERN MALTA telescope group
  - Engineering support by LBNL, CERN,…
  - ….

Summary

- ★ A sophisticated BCM' detector is being developed for ATLAS High-Luminosity upgrade
- ★ The status of the proposed design was presented
- ★ The preliminary performance satisfy the goals of ATLAS BCM':
  to protect the delicate ATLAS inner Silicon parts and to measure/monitor the luminosity and background
- ★ There is a challenging period in front of us to secure enough parts and manpower and produce the missing pieces for the installation in late 2025