The High-Granularity Timing Detector for ATLAS at HL-LHC

ICHEP 2024

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on behalf of the ATLAS HGTD Group

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KTH VETENSKAP OCH KONST

ATLAS EXPERIMENT

High-Granularity Timing Detector

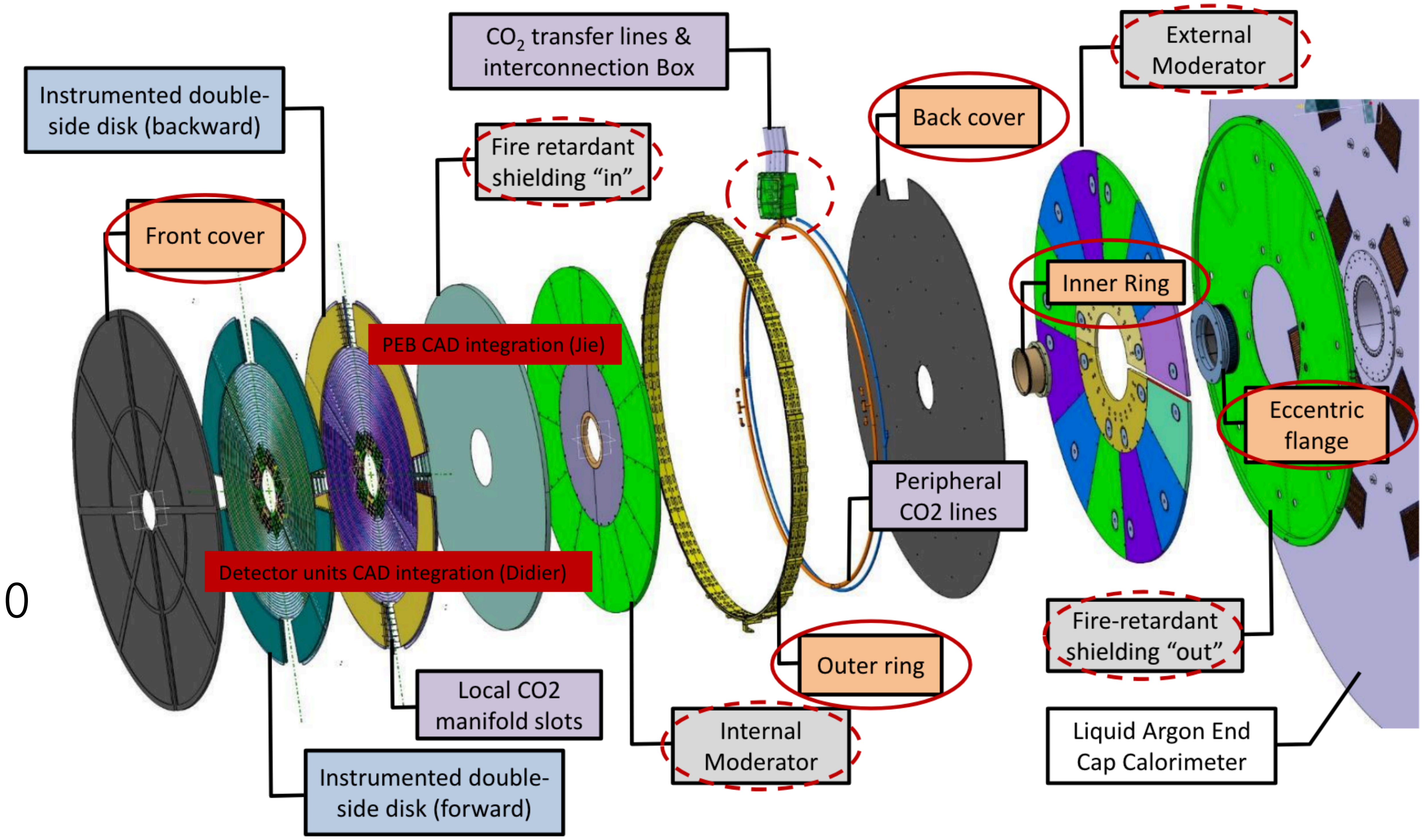
HGTD will provide:

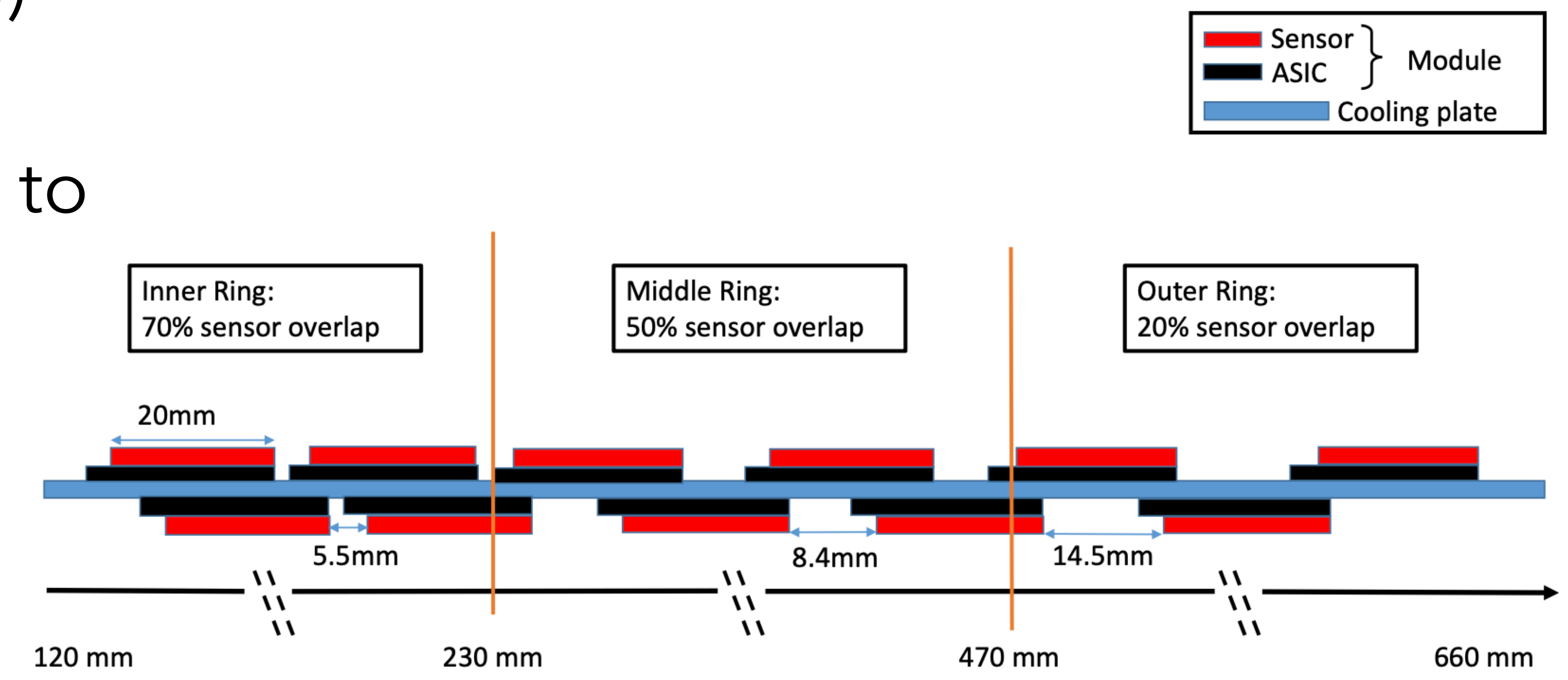
- **Timing** information for charged particles with an expected per-hit resolution of **<50-70 ps** over full lifetime
  ↠ *per-track resolution of **<35-50 ps** due to overlap*
- **Luminosity** measurement by reading hit counts at 40 MHz in outer region

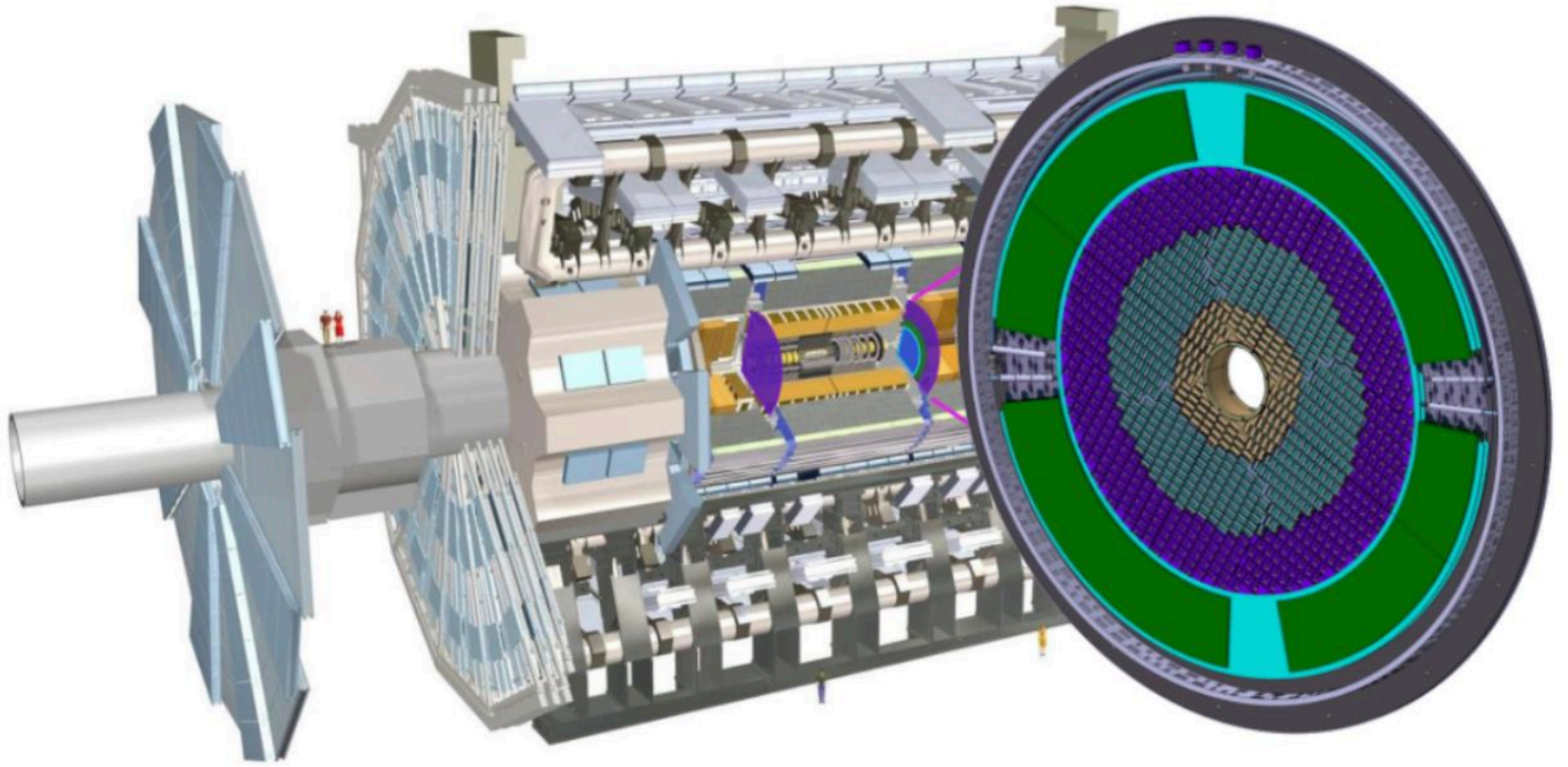
Located at z = ± 3.5 m from IP, covers forward region $2.4 < |\eta| < 4.0$ ($2.4 < |\eta| < 2.8$ for luminosity readout)

Each end-cap consists of two double-sided disks, in total 8032 modules (3.6M readout channels)

Required to be radiation hard up to $2.5 \times 10^{15}\ n_{eq}/cm^2$ (replacements of "inner -" and "middle ring" needed!)



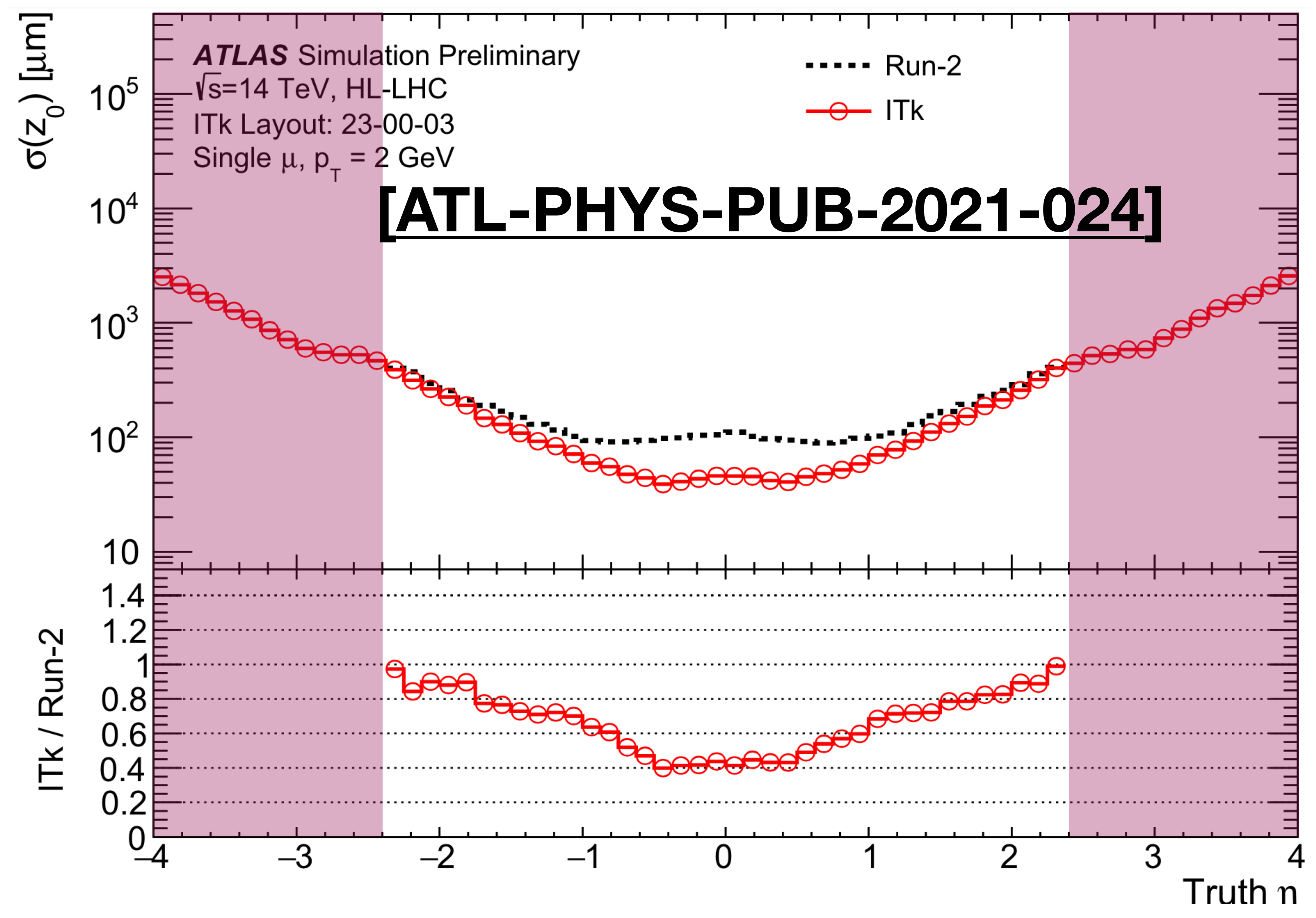


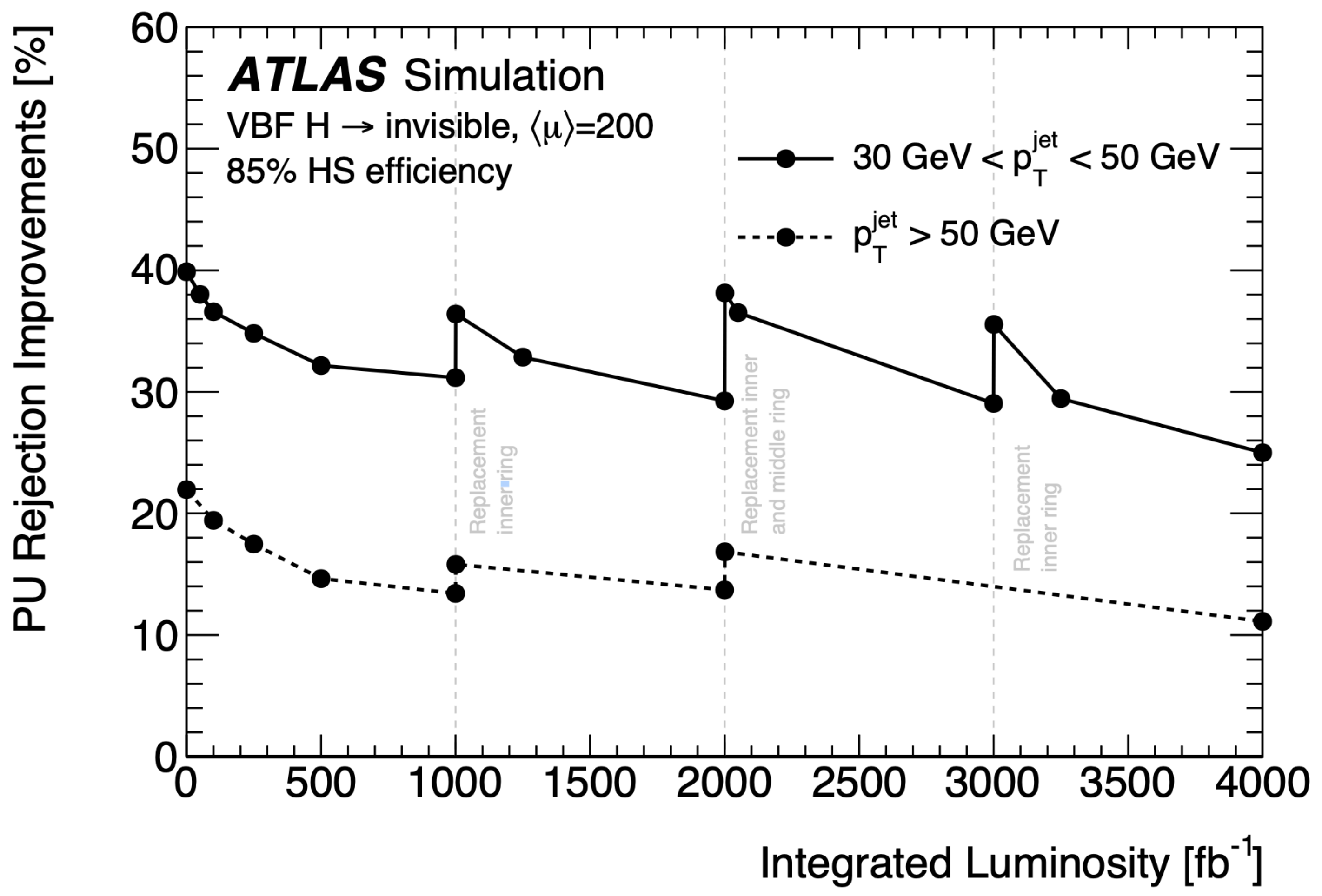


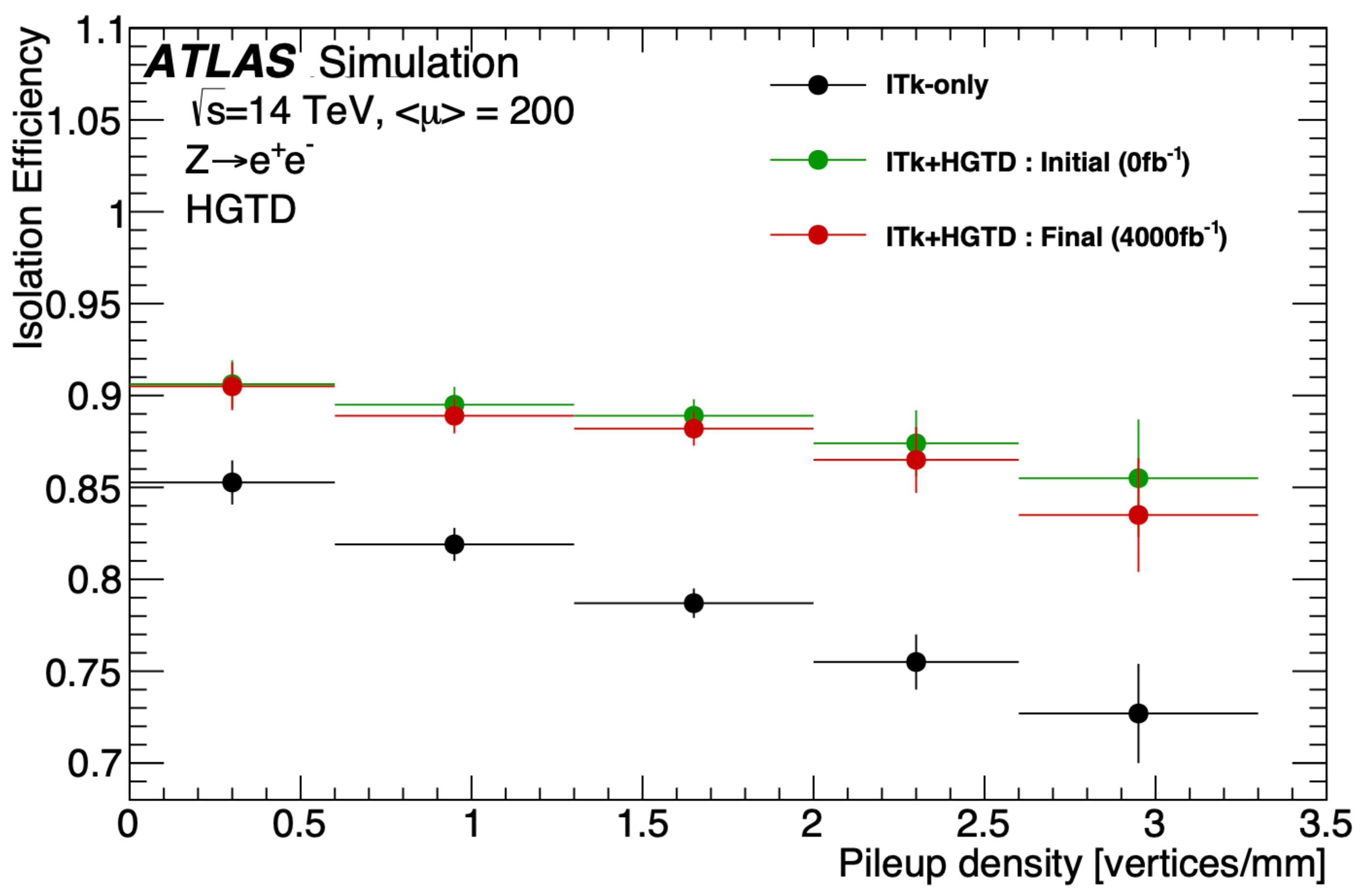
An additional dimension…

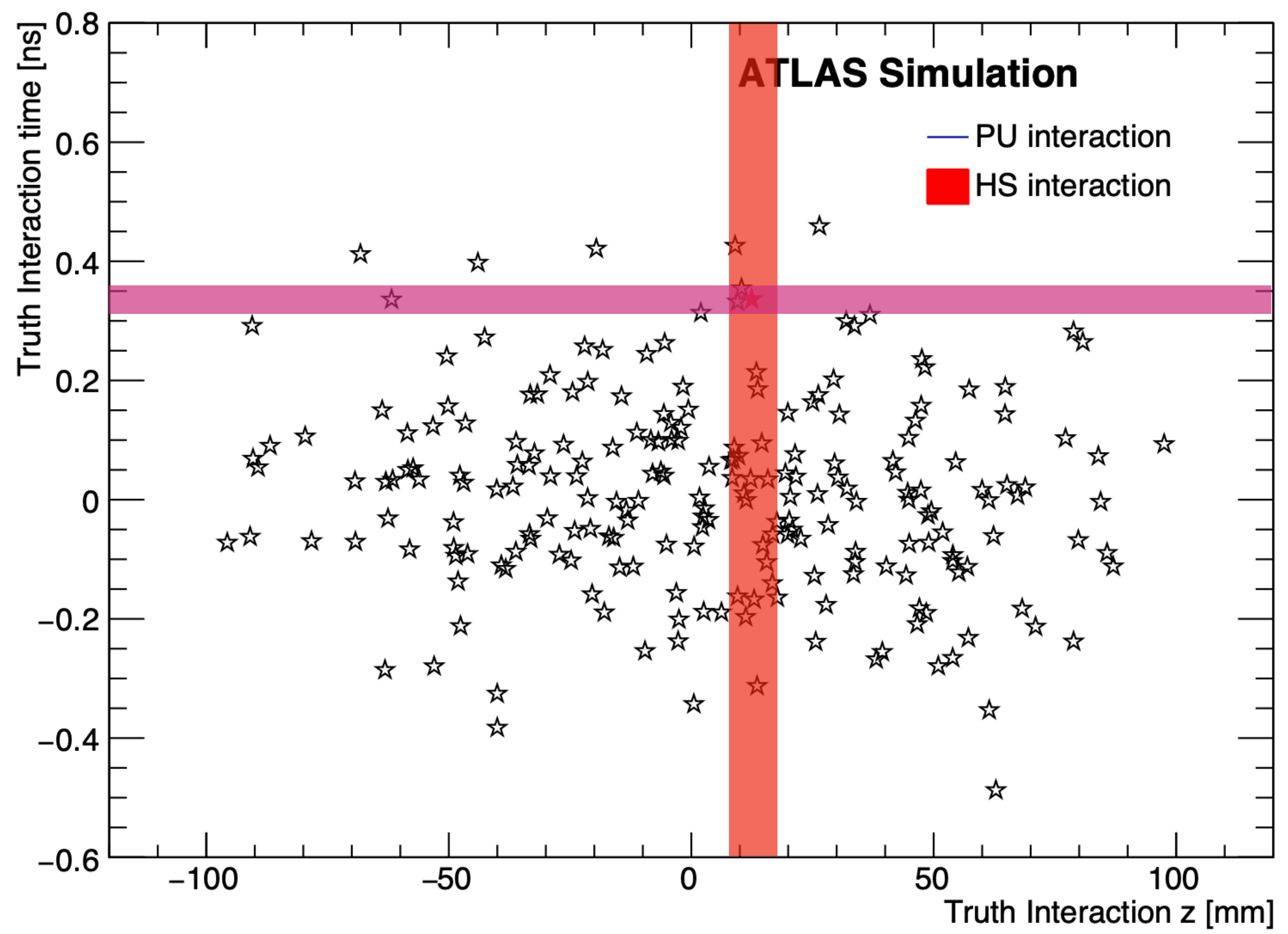
… for tackling the pile-up challenge:
At <μ> ~ 200, unambiguous track-vertex association challenging, especially in forward region where impact parameter resolution worsens

Adding time information will allow to recover performance in the forward region, applied to e.g. pileup-jet rejection or lepton isolation









Luminosity

Linear correlation between occupancy and number of interactions

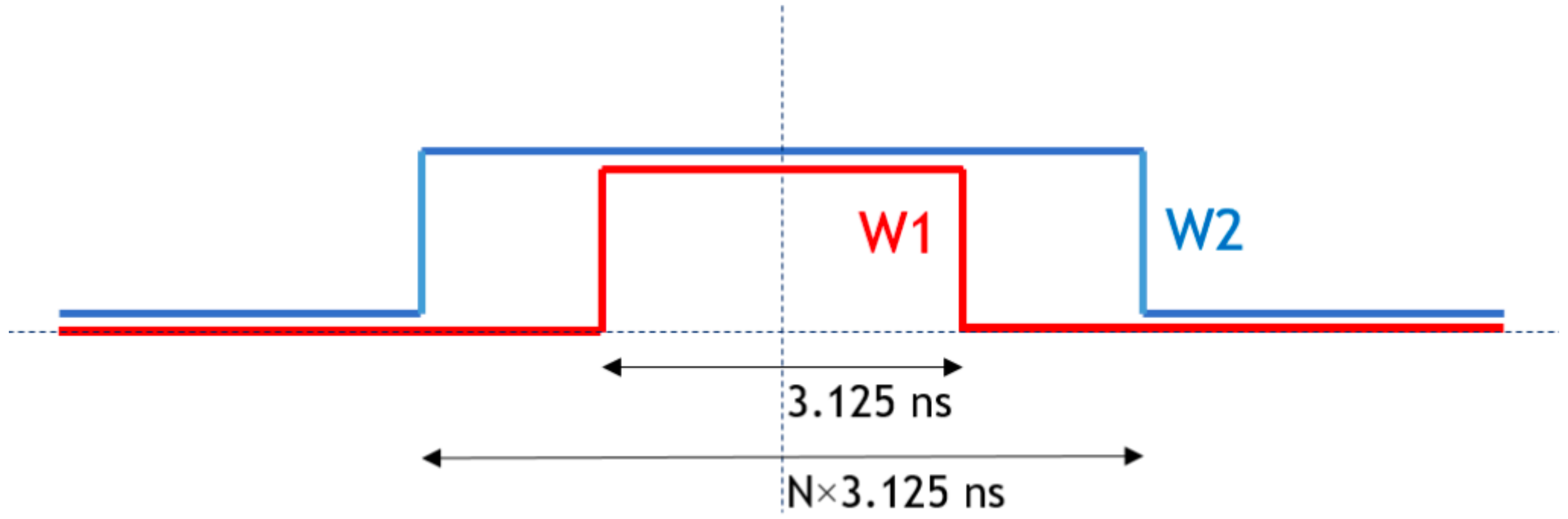
Luminosity data: Number of hits in central window read per bunch crossing from each ASIC in the region of **2.4 < |η| < 2.8** (8512 channels = 4256 modules!)

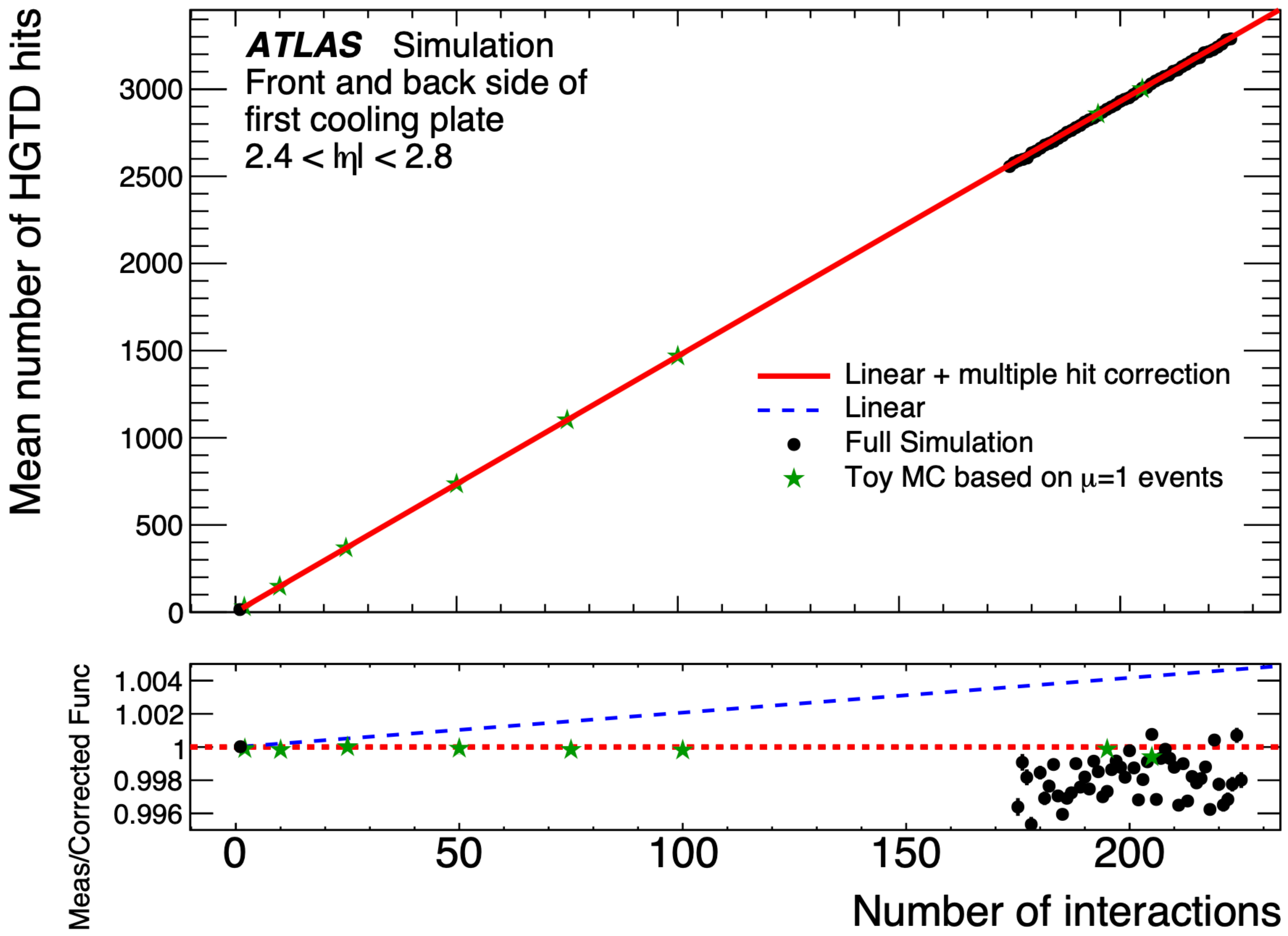
Additionally hit counts in larger time window recorded, used to determine backgrounds (e.g. afterglow)

Lumi data sent constantly at 40MHz via dedicated readout channel (= for **each bunch crossing!**), independent of trigger

Allows also per-bunch crossing **online** luminosity measurement (hit counts are accumulated in off-detector electronics to provide sufficient statistics)

Important contribution to reach ATLAS target of <1% luminosity uncertainty!



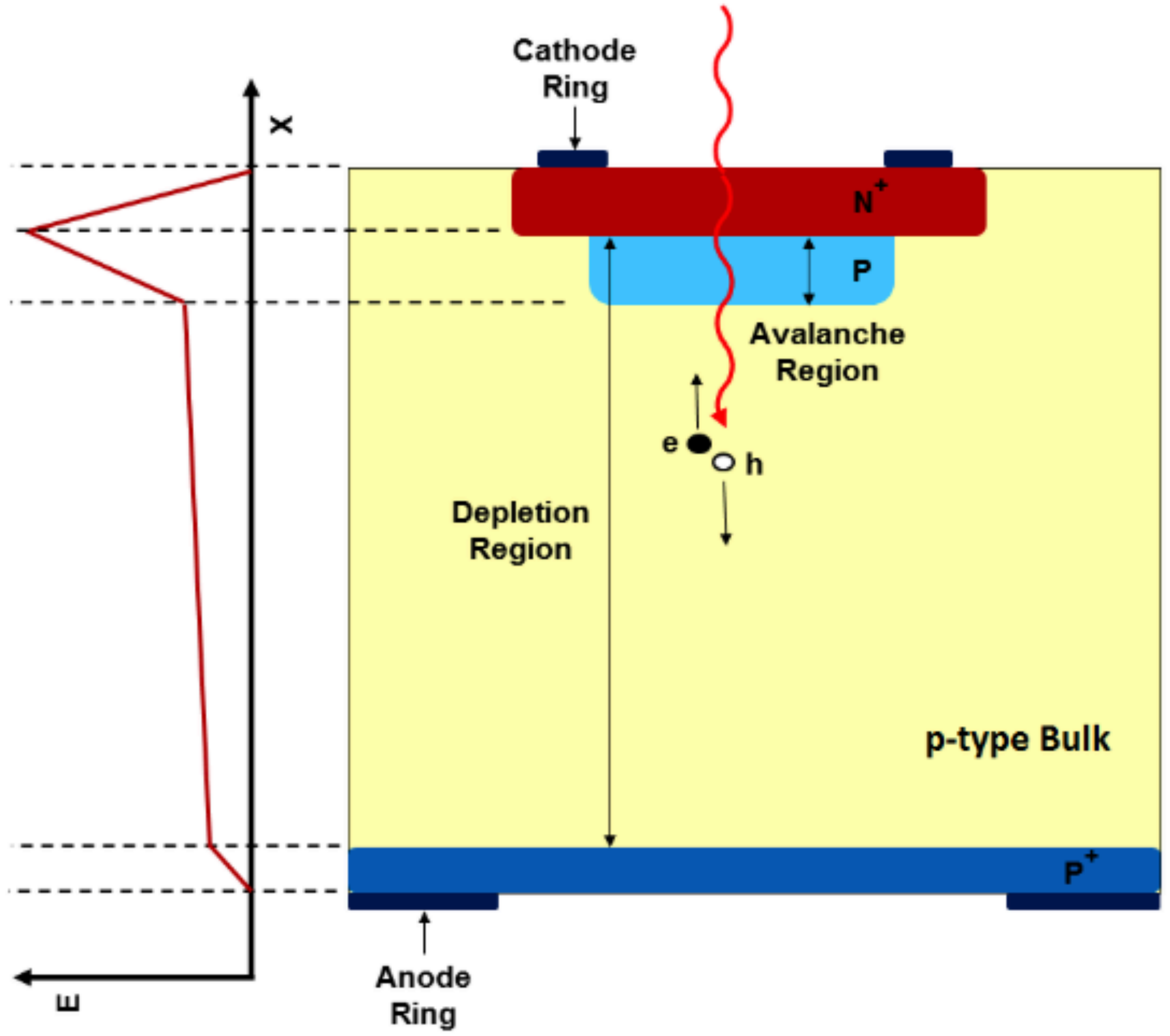


→ more on ATLAS Luminosity at HL-LHC during Christian Ohm's talk!

Sensors (LGAD)

Technology chose for HGTD is the **L**ow **G**ain **A**valanche **D**etector

n-on-p silicon sensors with additional p-implant (gain of 10-20)



Basic requirements:

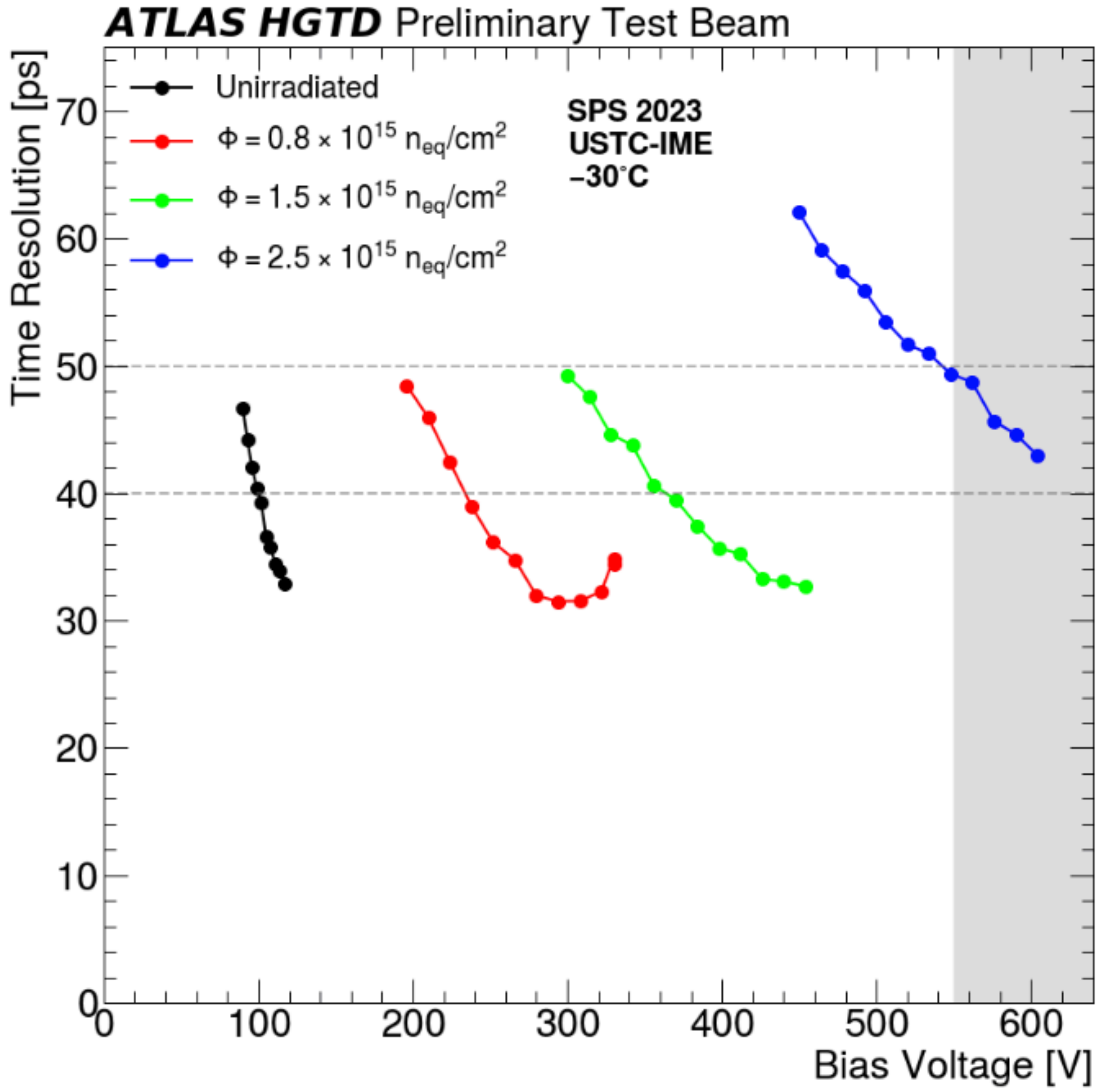
- withstand maximum fluence of 2.5 x 10^{15} n_{eq}/cm^2 (TID of 2 MGy)
- time resolution <40 ps (< 50 ps)
- collected charge of >15fC (> 4 fC)
- efficiencies of 97% (95%)

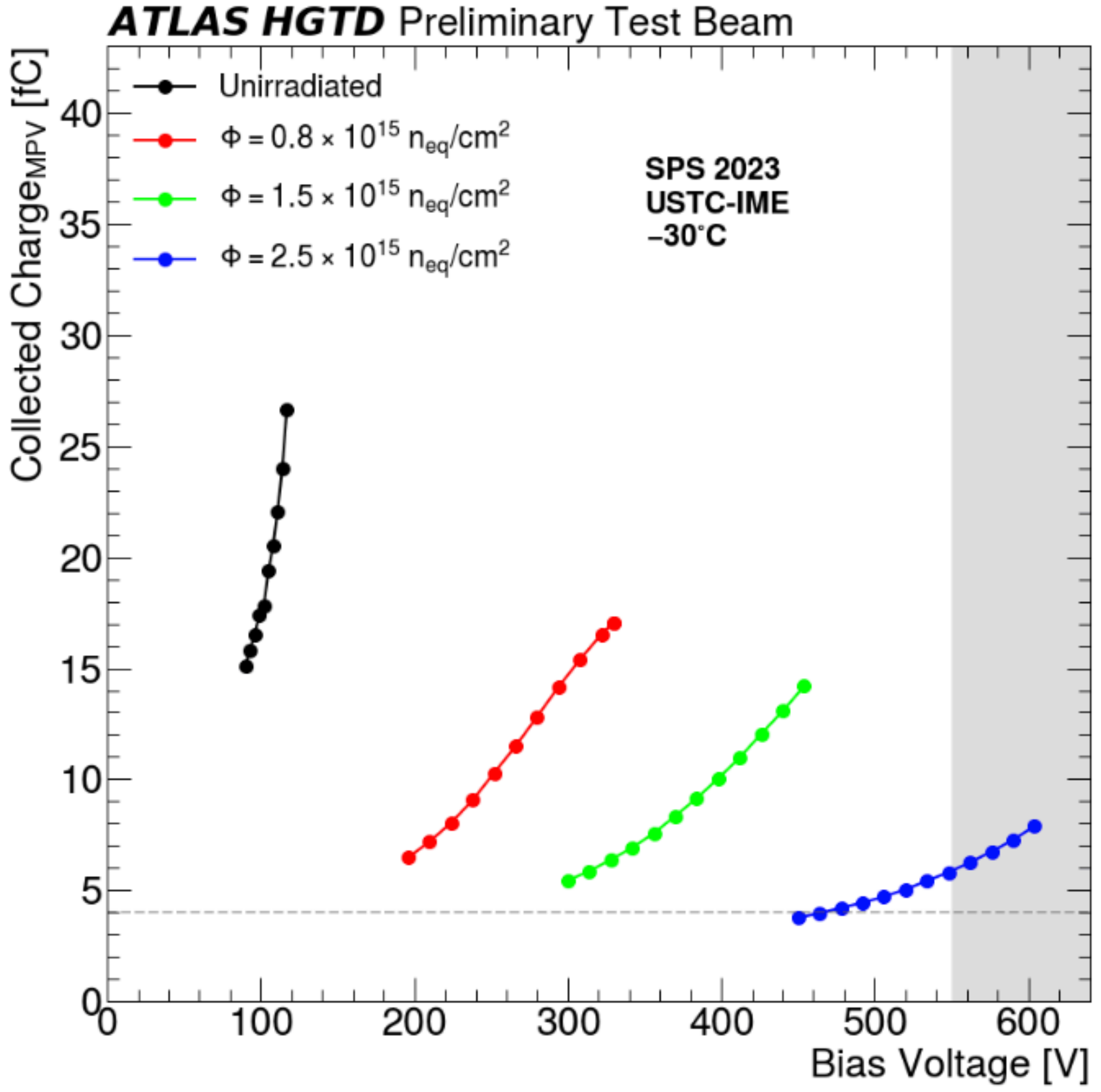
Active thickness of 50 µm, pixel size of 1.3 x 1.3 mm^2

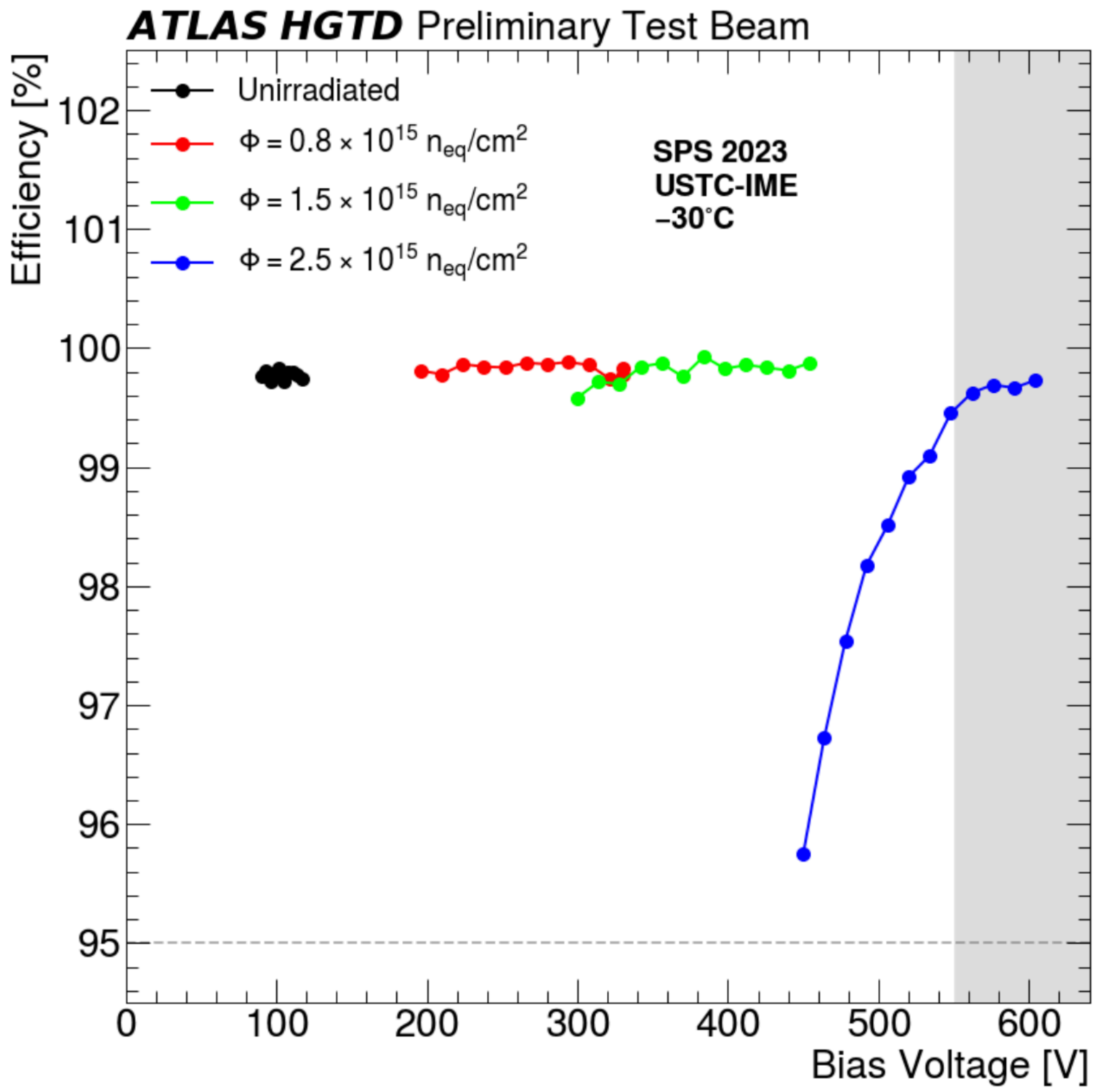
Sensor matrix with 15 × 15 pixels

~16k sensors will be needed for HGTD, produced by IHEP-IME and USTC-IME

Pre-production sensors available since last year, so far within specifications

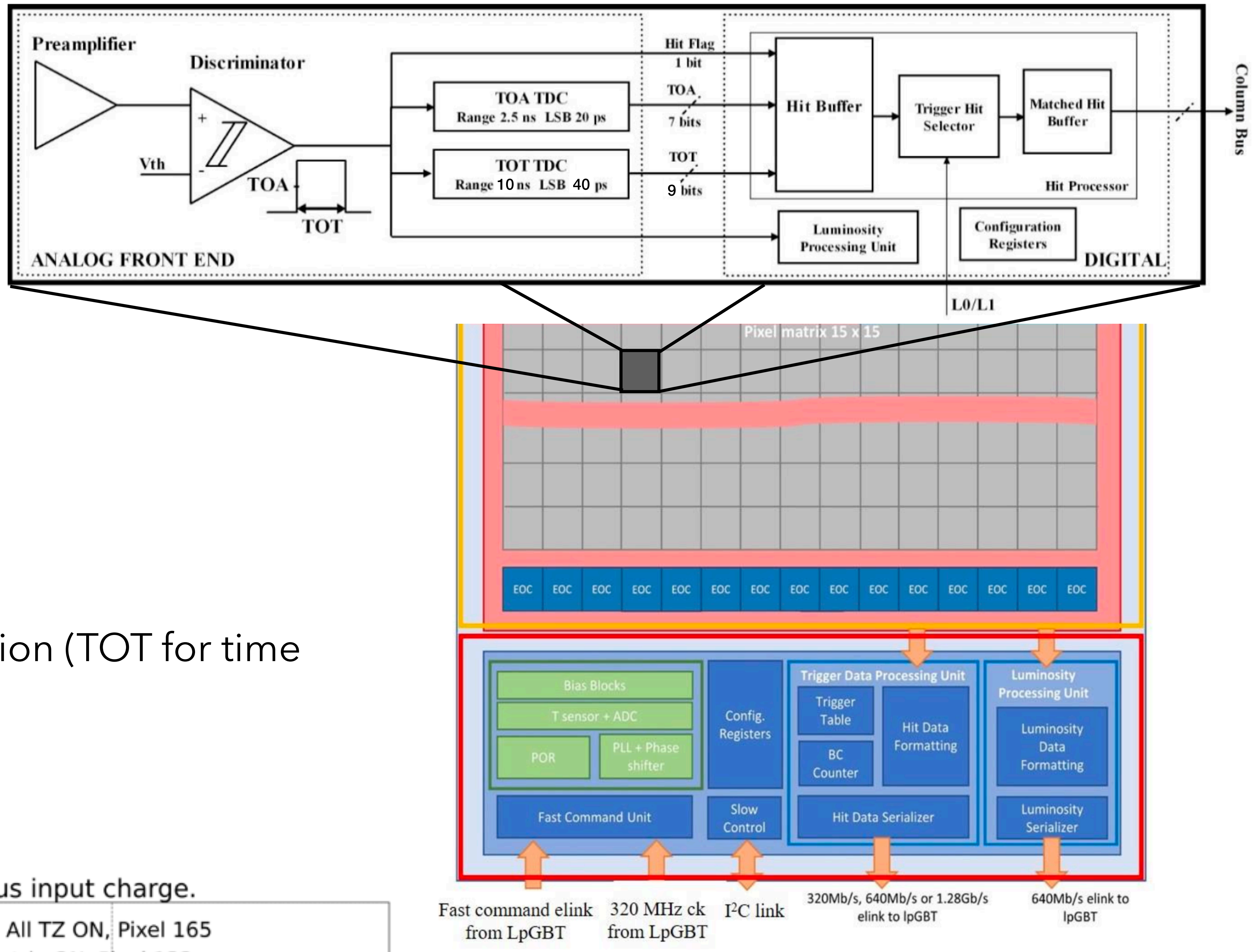






Front-end ASIC

on-pixel electronics

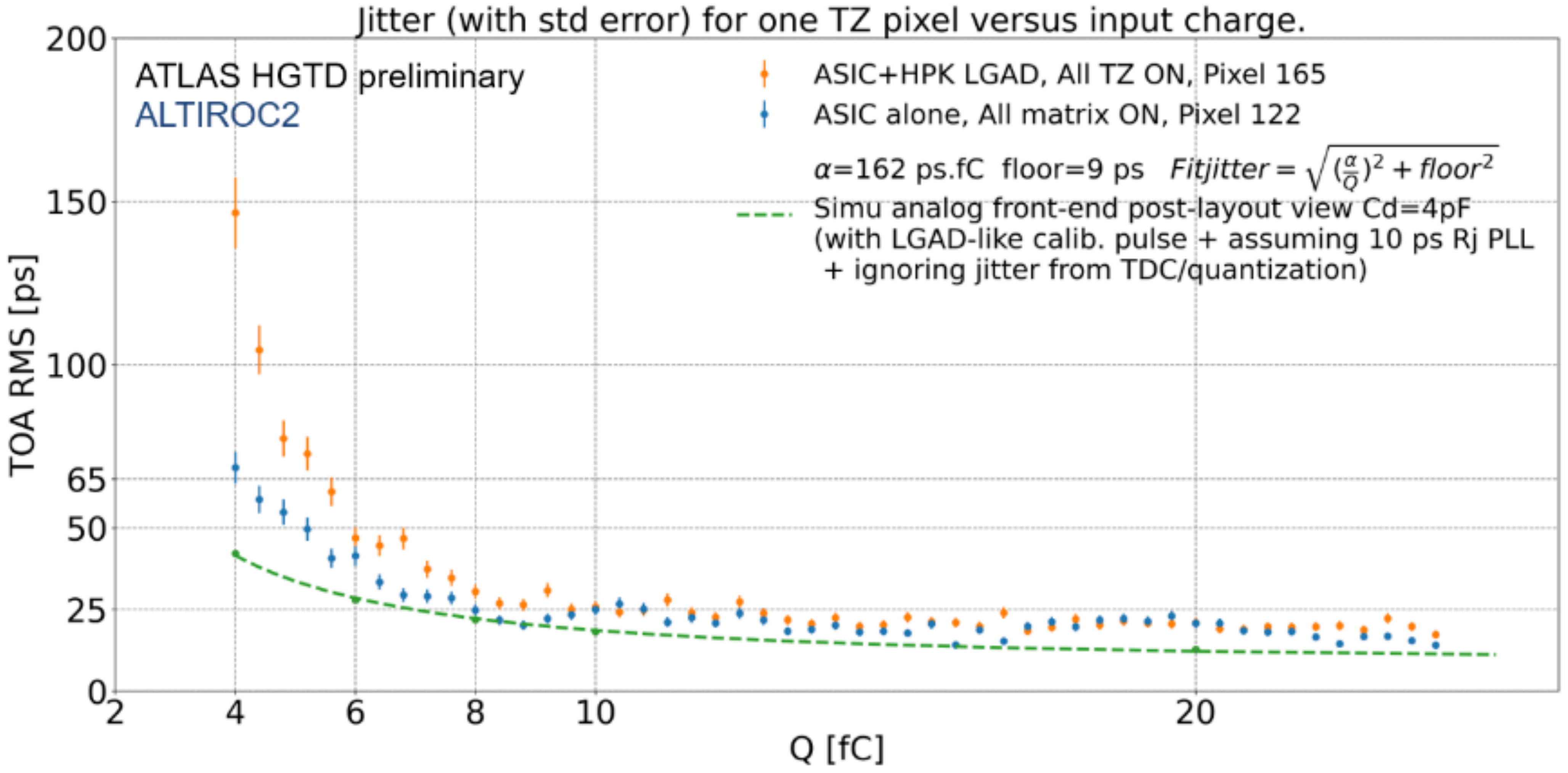


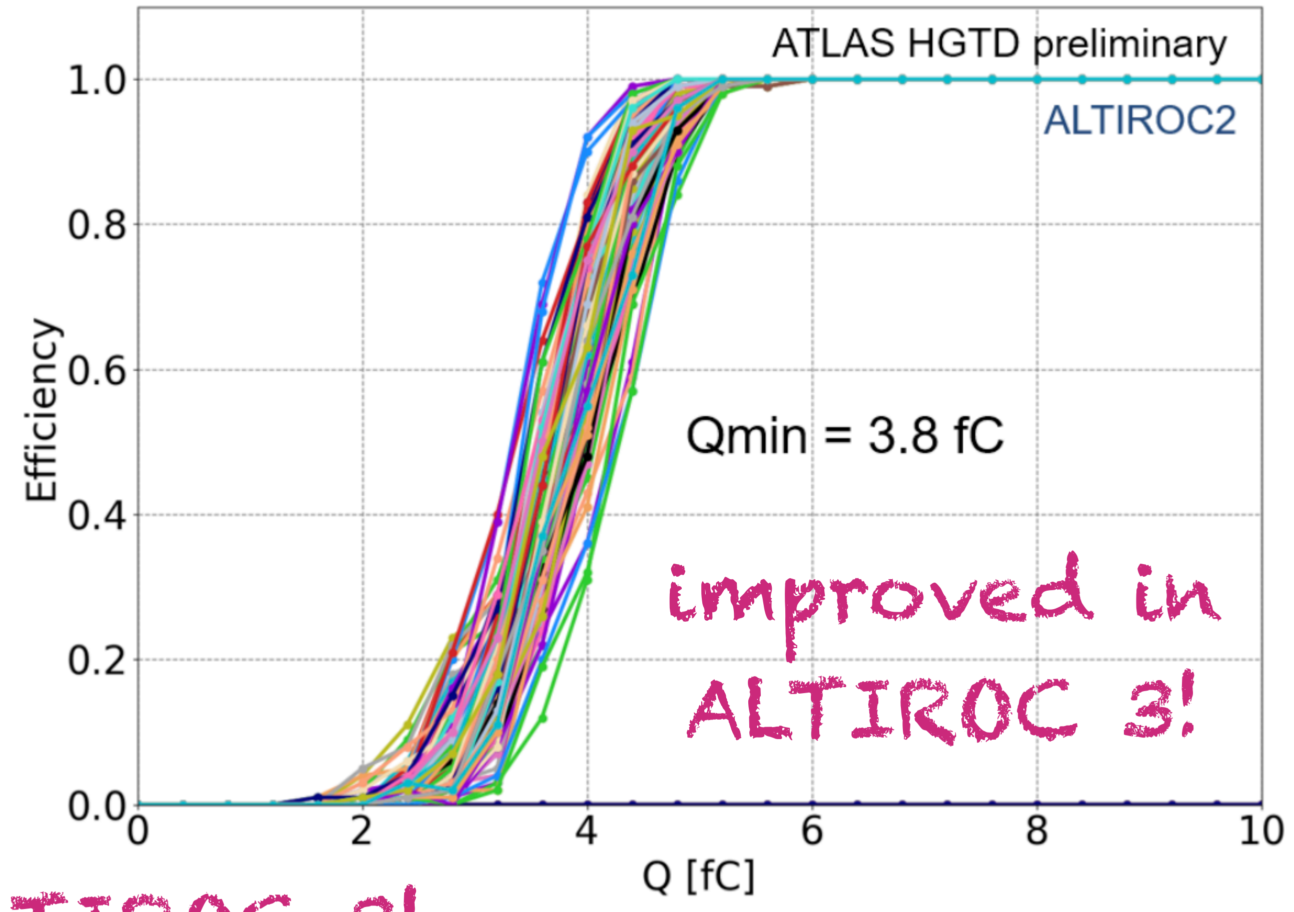
ATLAS **L**GAD **T**iming **I**ntegrated **R**ead**O**ut **C**hip (ALTIROC)
produced in 130 nm CMOS process by TSMC

Basic requirements:
- Radiation hard up to 2.0 MGy
- Small jitter: 25 ps at 10 fC (< 65 ps at 4 fC)
- 2 fC minimum discriminator threshold

15x15 pixel matrix, TDC conversion for TOA and TOT per pixel with a 20ps and 40ps resolution (TOT for time walk correction)
Luminosity information (number of hits) sent for two different configurable time windows

Several versions of the ASIC over R&D phase:
- ALTIROC 0&1: single pad prototypes for testing analog fronted part
- ALTIROC 2: full sized (15x15) ASIC, VPA & TZ amplifier types
- ALTIROC 3: radiation hard, performance up to specifications
- ALTIROC A: (pre-)production ASIC, first test beam results expected this autumn

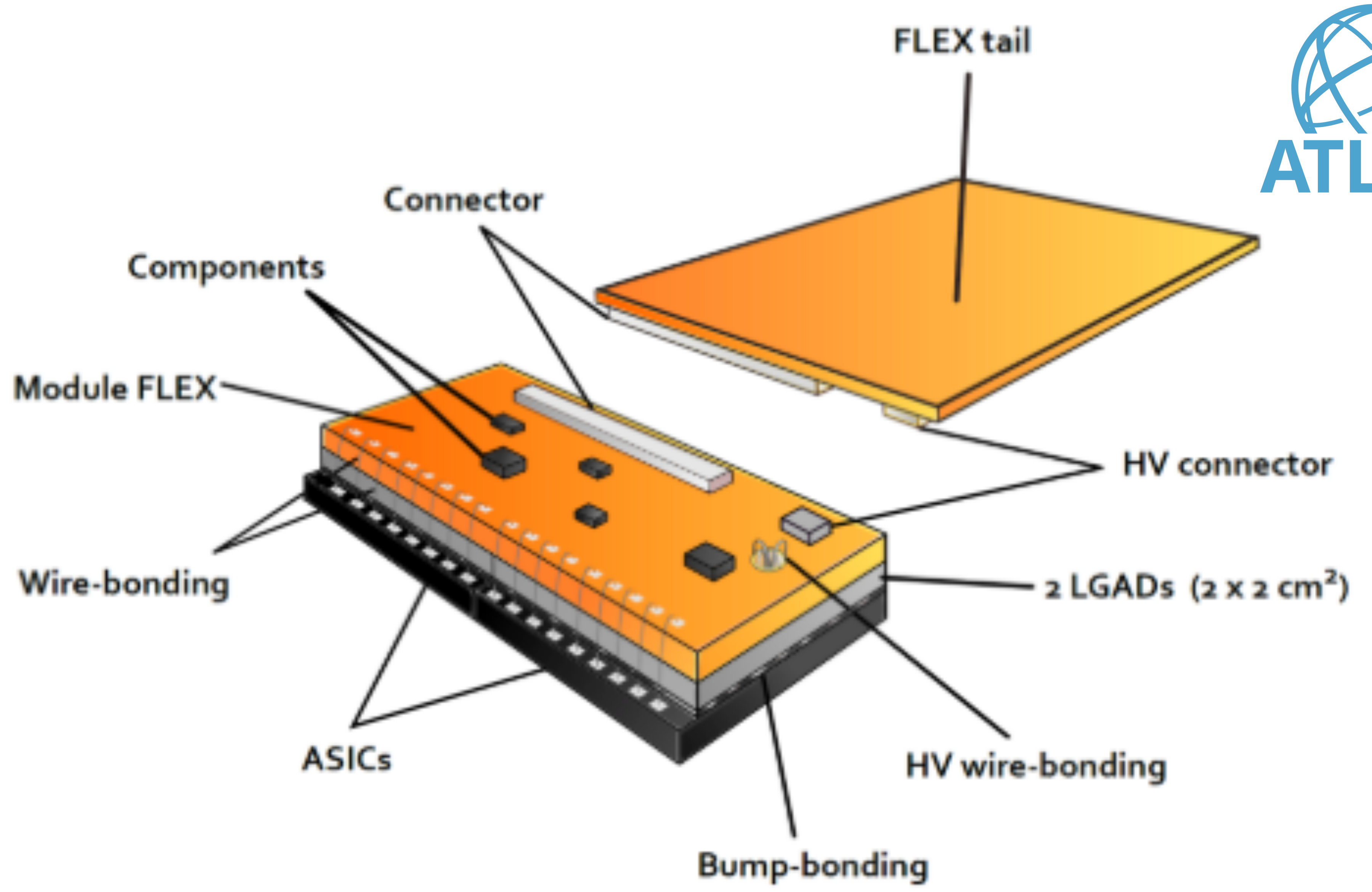




→ Please have a look Xiao Yang's poster on test beam performance with ALTIROC 3!

Modules ...

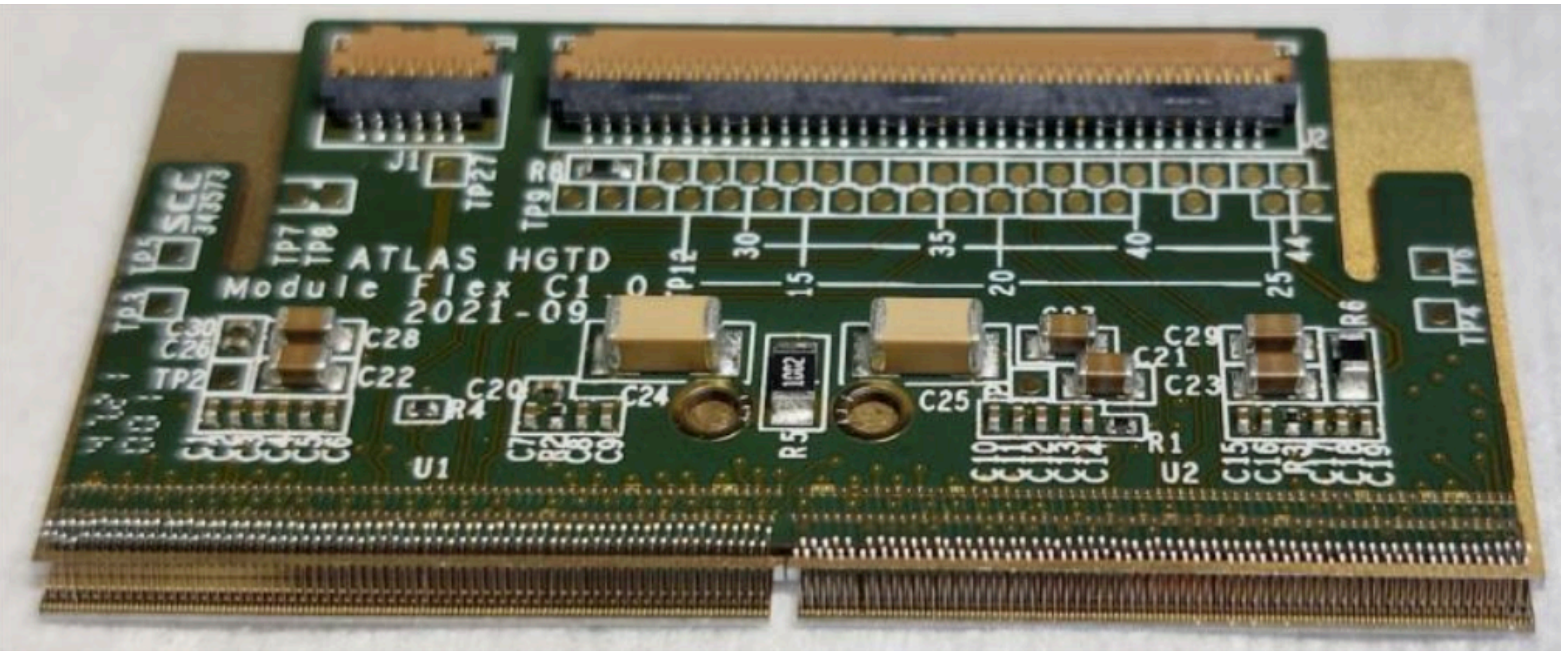
HGTD uses only one **module** design in the full detector, assembly in 6 different sites



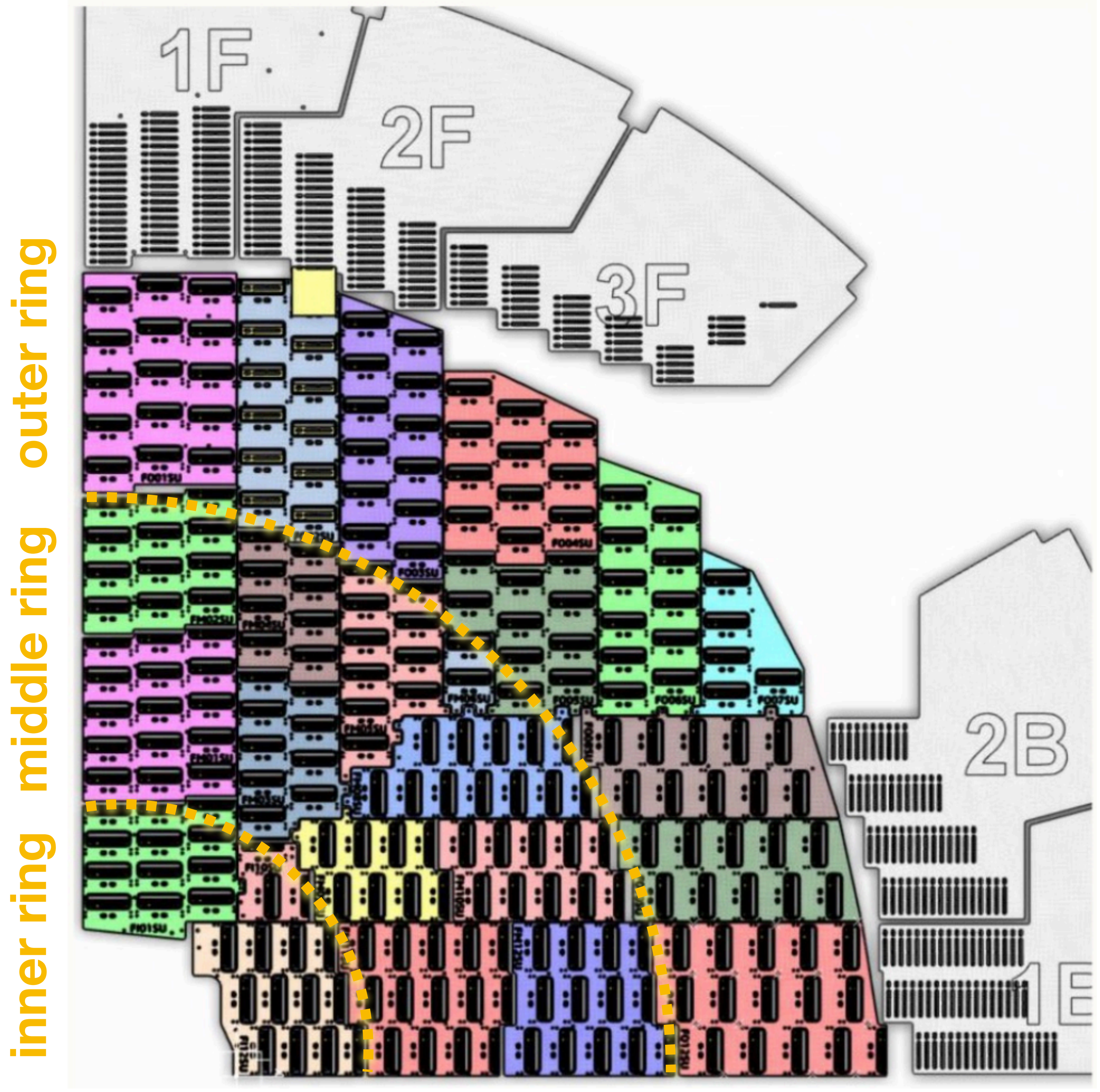
Dimensions: 2x4 cm^2 (15 x 30 channels), will be operated at -30 °C

Module consists of:

- **2 Hybrids**: ASICs bump bonded to LGADs (90μm bumps)
- **Module flex**: glued to hybrids and wire-bonded to ASICs



... and Detector Units



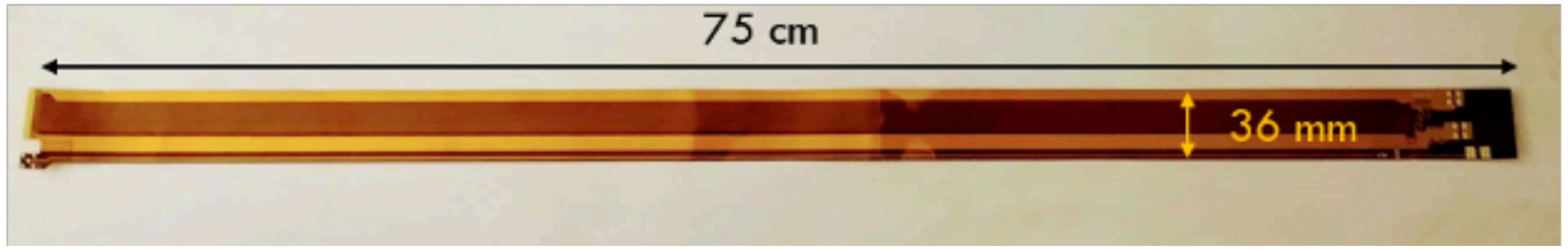
Modules are loaded on **support units** made of PEEK

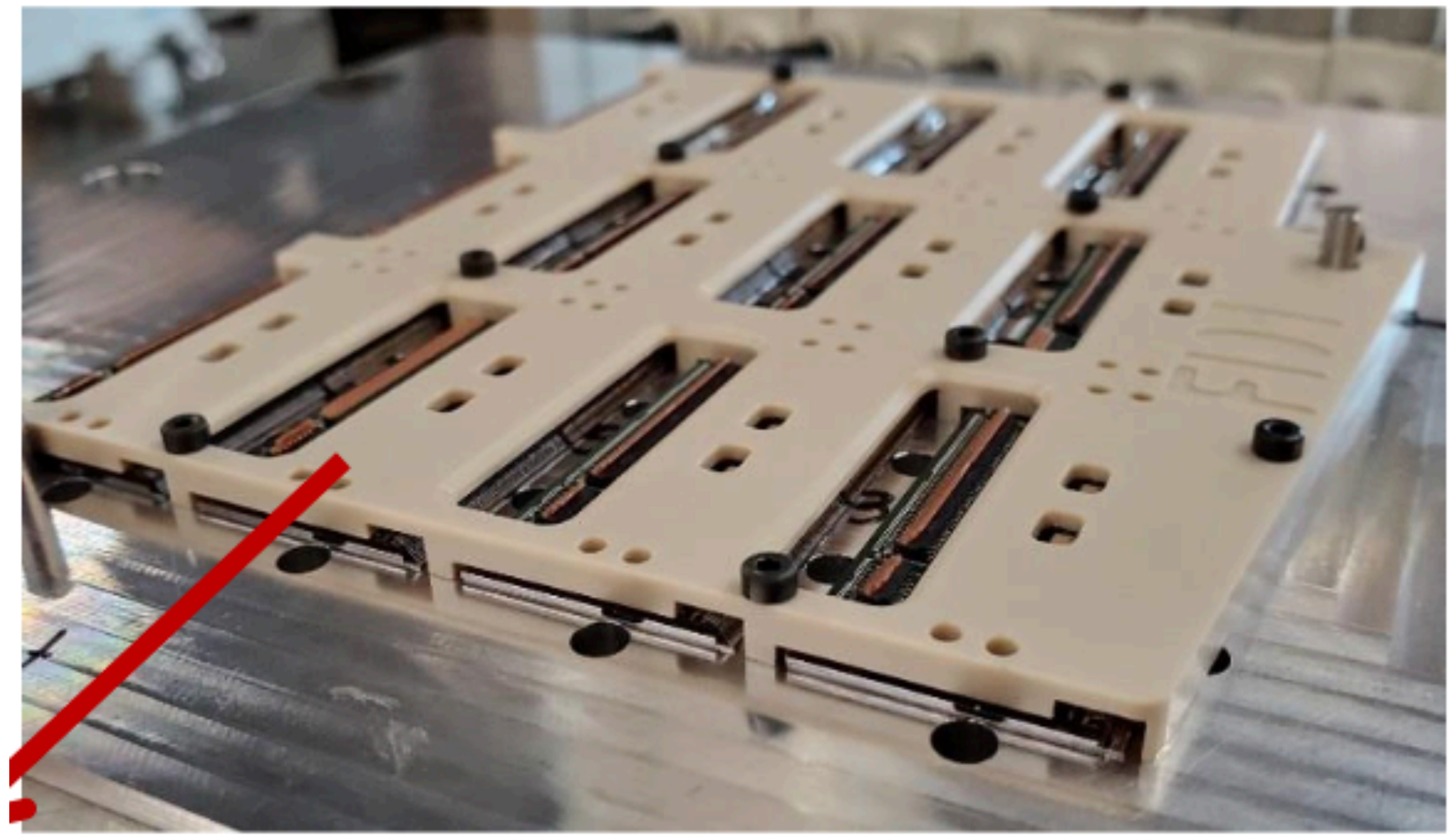
24 (front) + 24 (back) support unit designs to cover one quarter disk
↠ *will facilitate replacement of "rings"*

Assembly:

- Modules placed on aluminium base plate, held in place by vacuum pump
- Glue deposited on module & support unit lowered on top
- Loaded "**Detector unit**" screwed in place on the cooling disk of HGTD

Modules are connected via "FLEX tail" cables to peripheral electronics boards





Peripheral electronics board (PEB)

On-detector electronics responsible for:

- Control, monitoring, data aggregation and transmission
- Power distribution (low & high voltage)
- NTC thermistor connection between the modules and the interlock system

Main components:

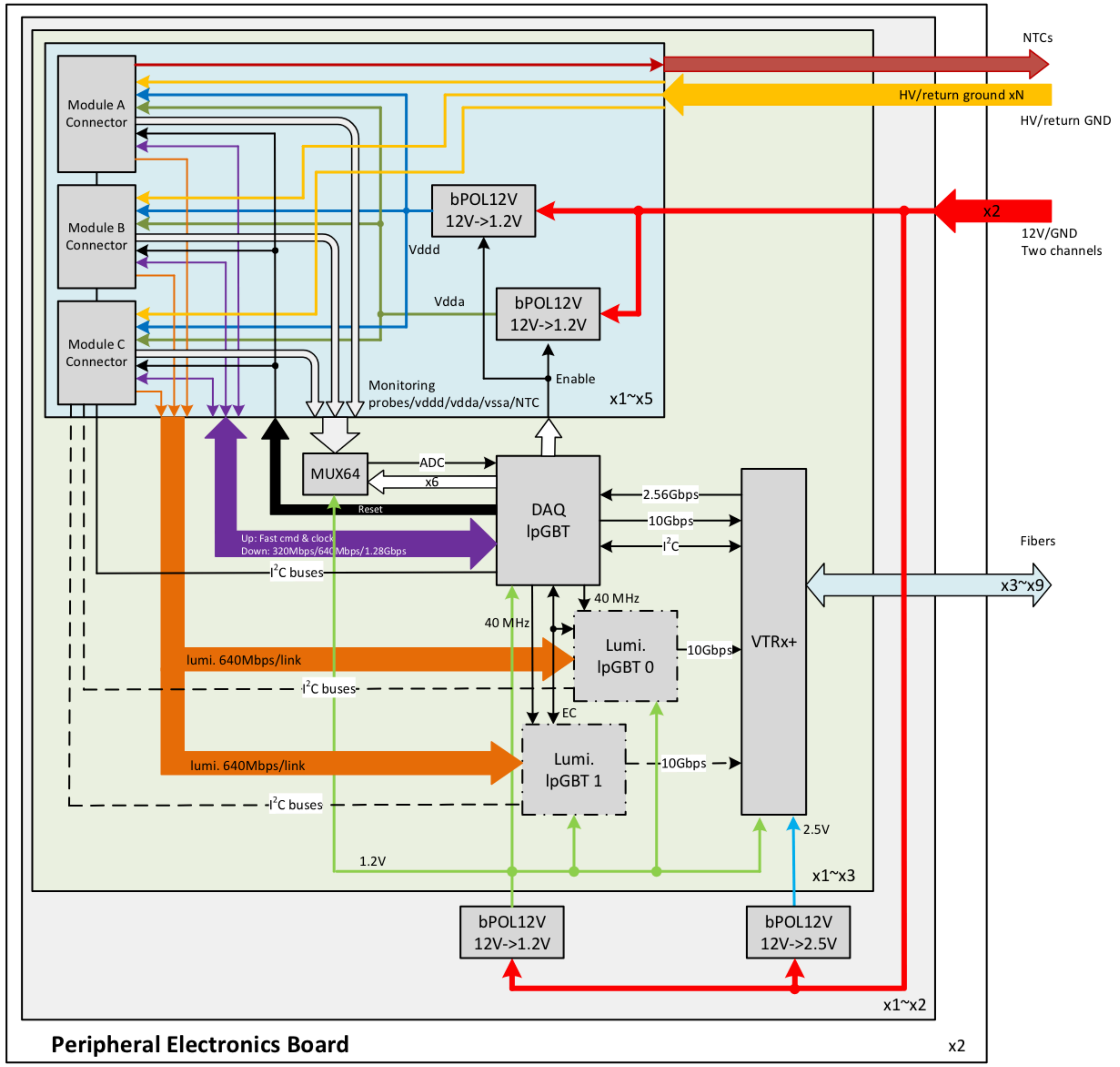
IpGBT: forwards fast commands & slow control to FEs, aggregates and forwards data to DAQ system (10.24 Gbps with FEC5) separately for timing & lumi data

VTRX+: translates electrical signals to optical

MUX64: multiplexer chip, monitoring probes read via ADC pins of IpGBT

bPOL12V : low voltage DC/DC converters

conceptual design



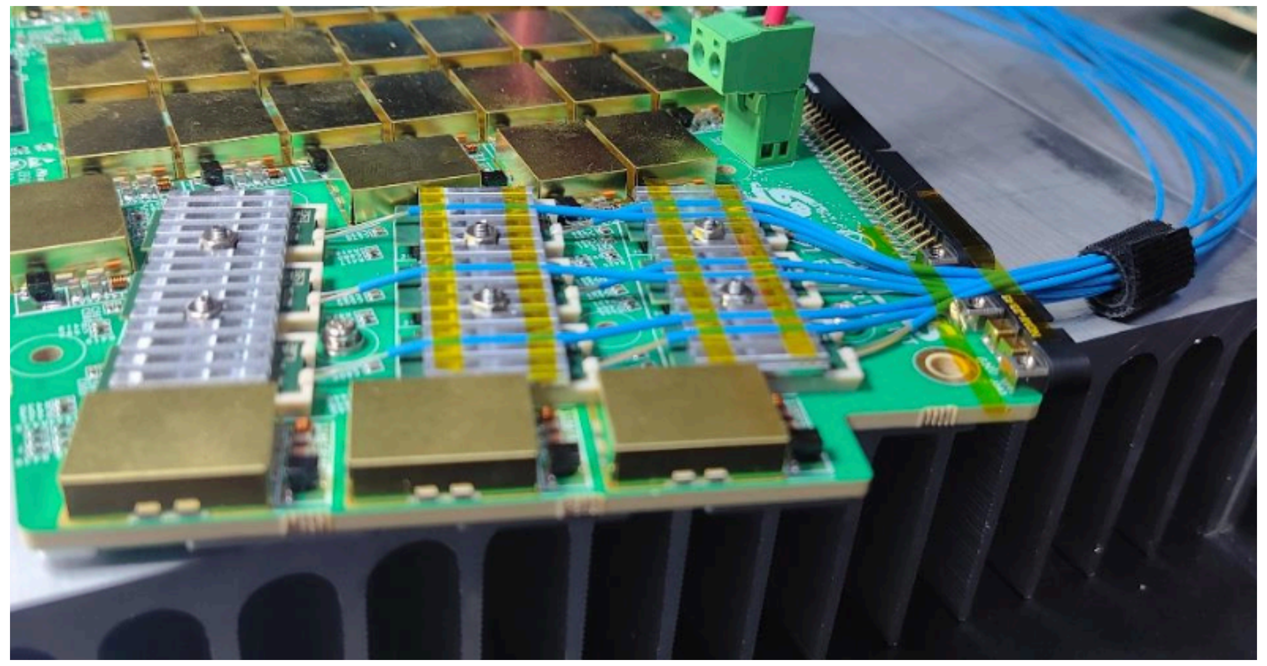
“PEB1F”

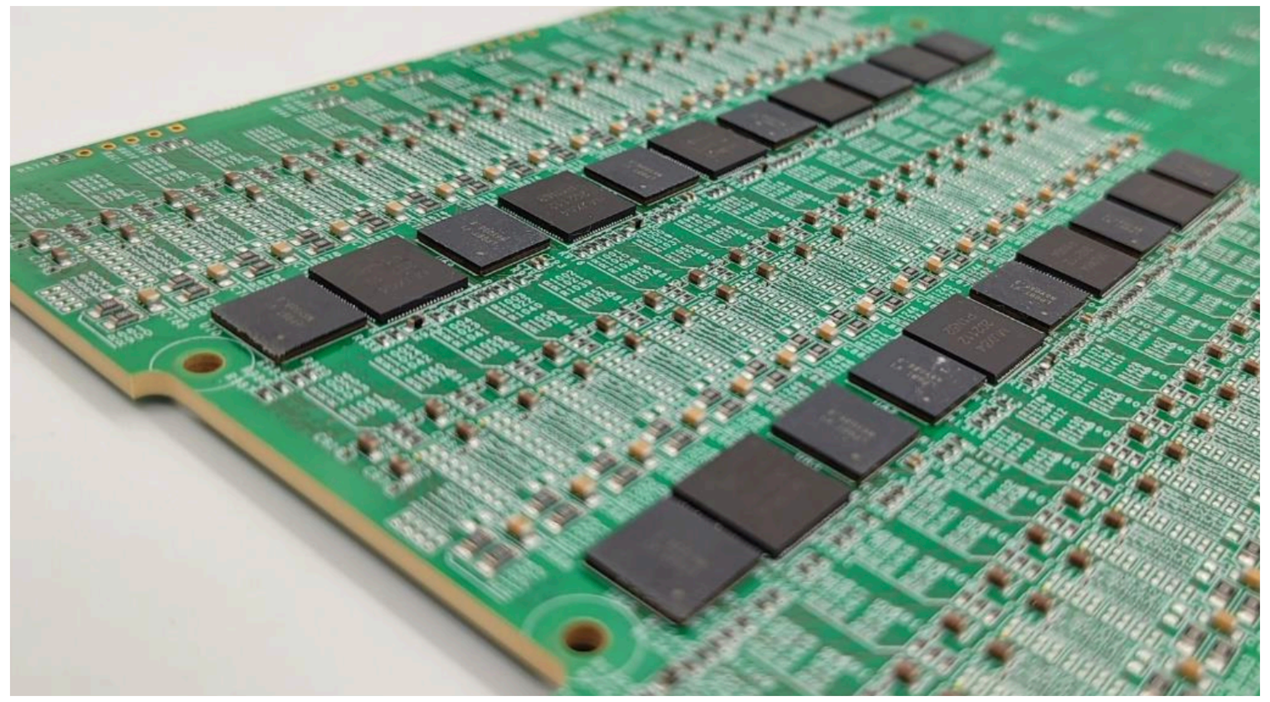
In total 5 PEB designs used to cover the full detector ↠ “PEB1F” as the most complex object selected to demonstrate feasibility

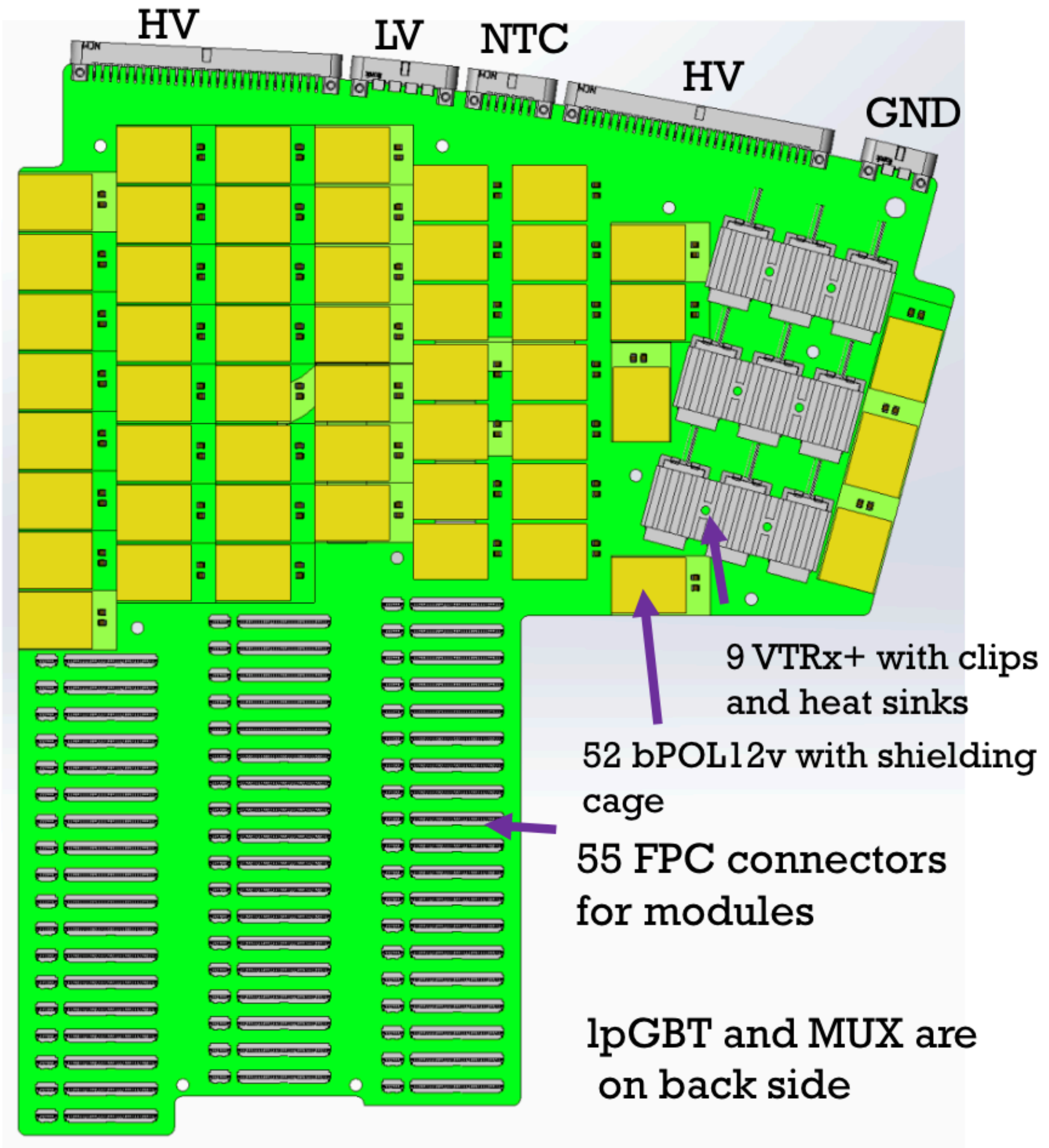
22 layer PCB, connects to 3 rows of modules

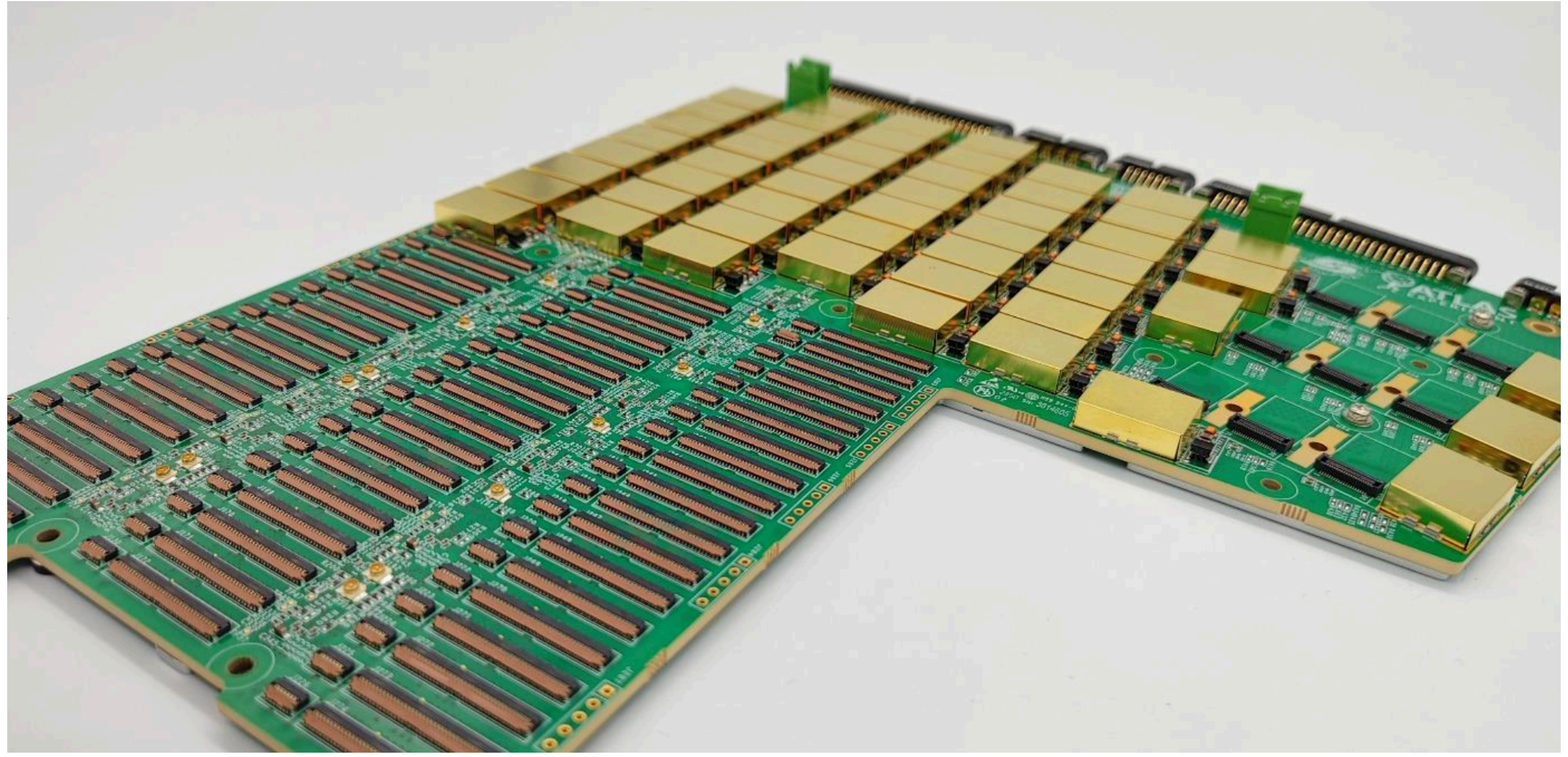
Components:

- 9 timing and 3 lumi lpGBTs
- 9 MUX chips
- 9 VTRX+
- 52 bPOL12V

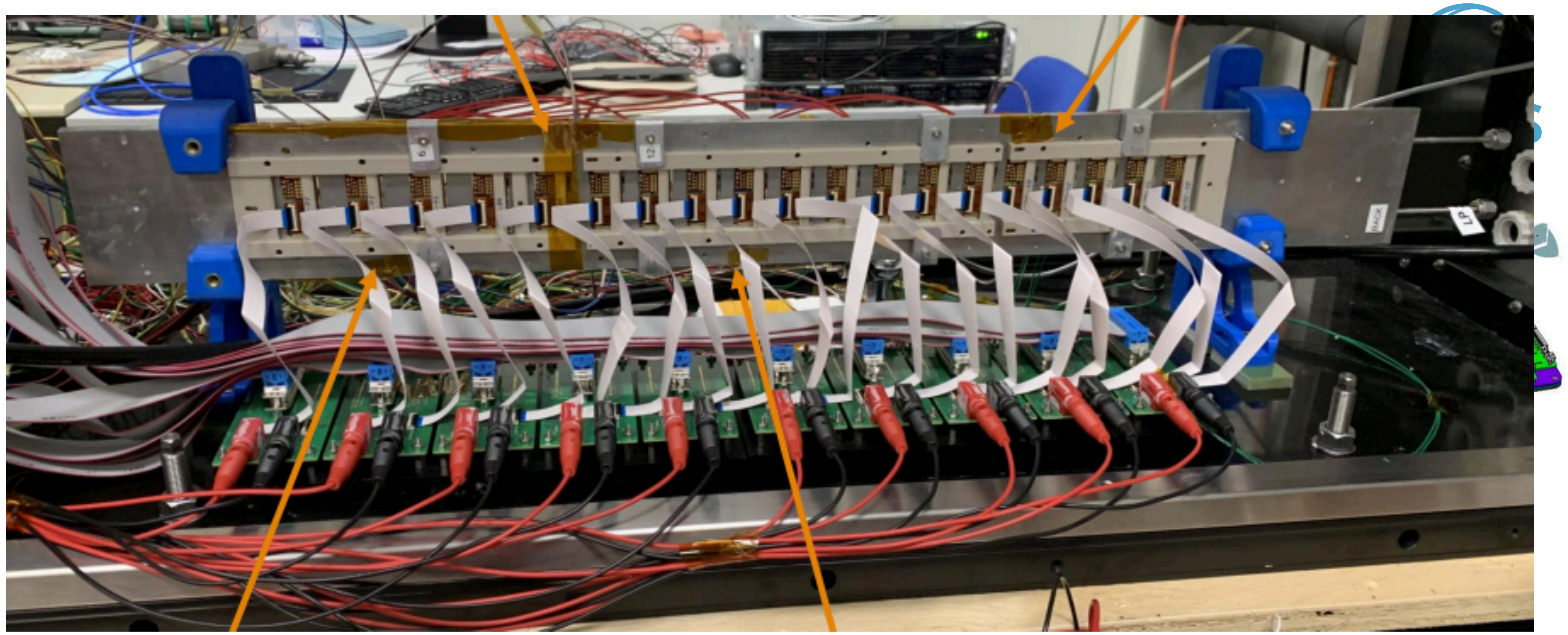








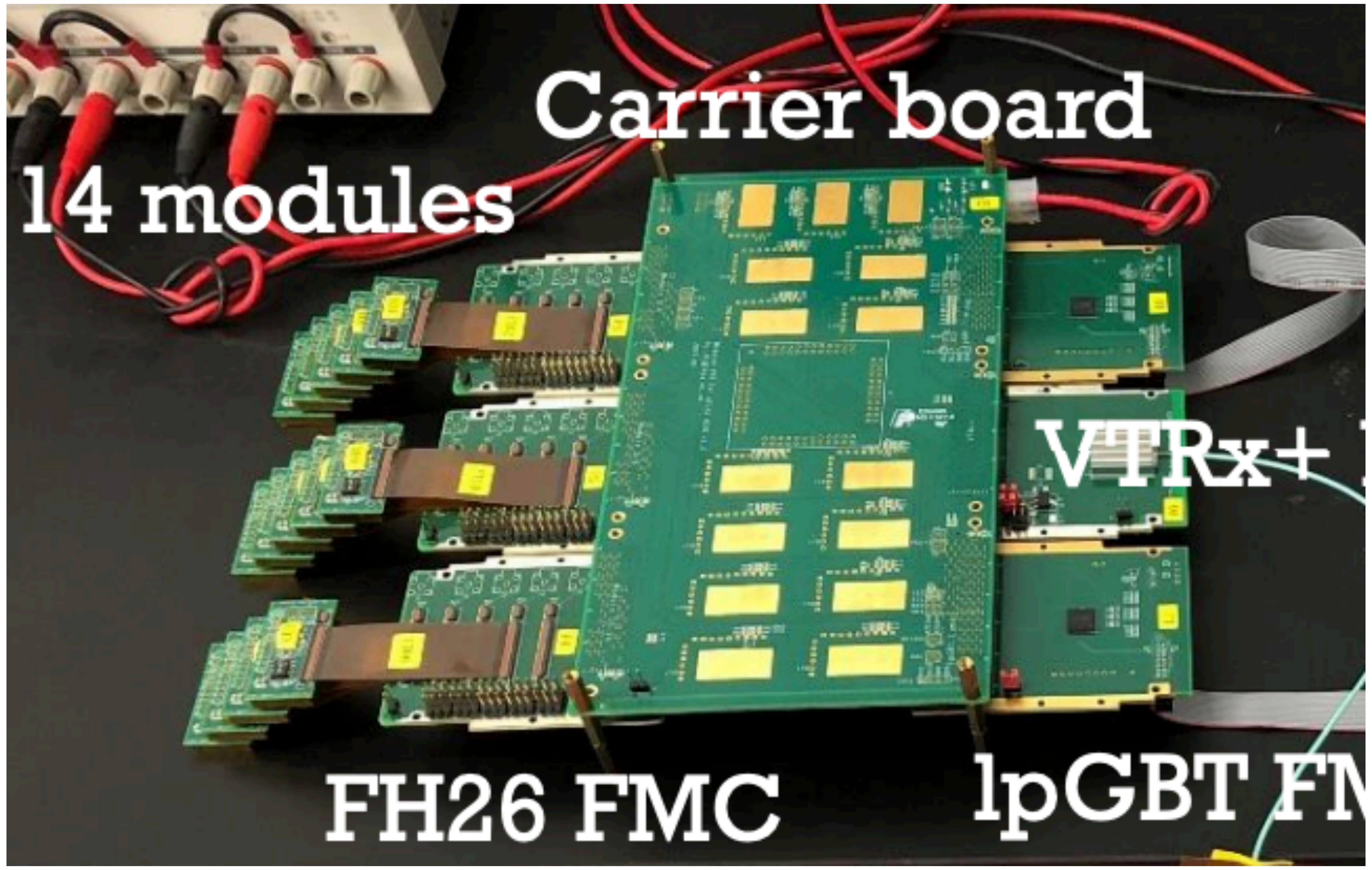
Demonstrator



Several demonstrator setups for testing specific aspects assembled

Heater demonstrator:
testing of CO2 cooling with realistic heat load

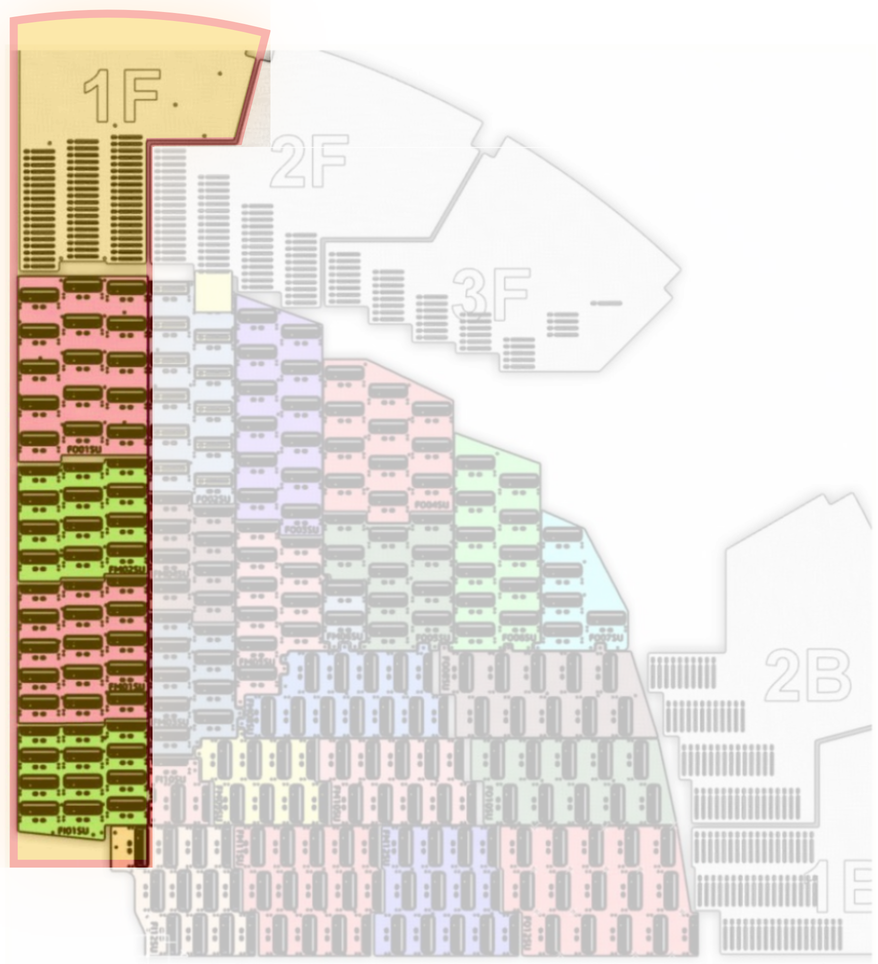
DAQ demonstrator:
testing of full readout path from module to Phase 2 readout cards (FELIX), using the final components of the PEB

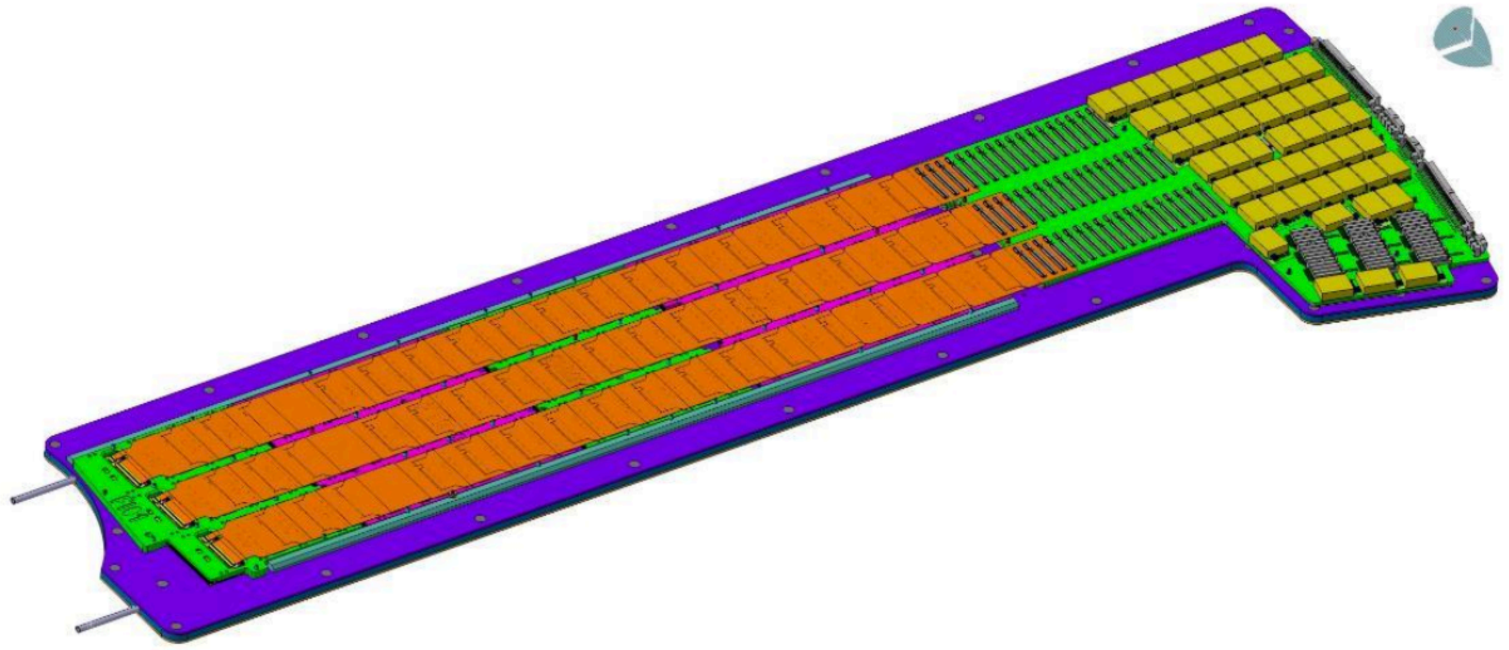


Demonstrator

"Full demonstrator" project brings all components together

- 1 PEB connecting to 3 full readout rows, mounted on a cooling plate
- 54 modules (loaded on 4 support units) will be mounted in total





Integration & testing of LV&HV supplies and interlock system

Development of DAQ SW and detector control system

↠ Allows important tests of all components at *system level*

Summary

- HGTD will provide precision timing information for charged particles in the forward region of ATLAS during HL-LHC as well as function as a powerful luminosity detector
- LGAD sensors & ALTIROC front-end ASICs fulfil requirements up to a fluence of 2.5 x 10^{15} neq/cm2
- Loads of work going into design & testing of mechanical components, services, power supplies, interlock system, cooling system, development of assembly procedures as well as continuous test beam campaigns
- "Full demonstrator" setup bringing all components together for the first time
- R&D slowly coming to an end, moving towards mass production and construction of HGTD

BACKUP

LGAD single event burnout

Single Event Burnout – Catastrophic failure in highly irradiated LGAD devices

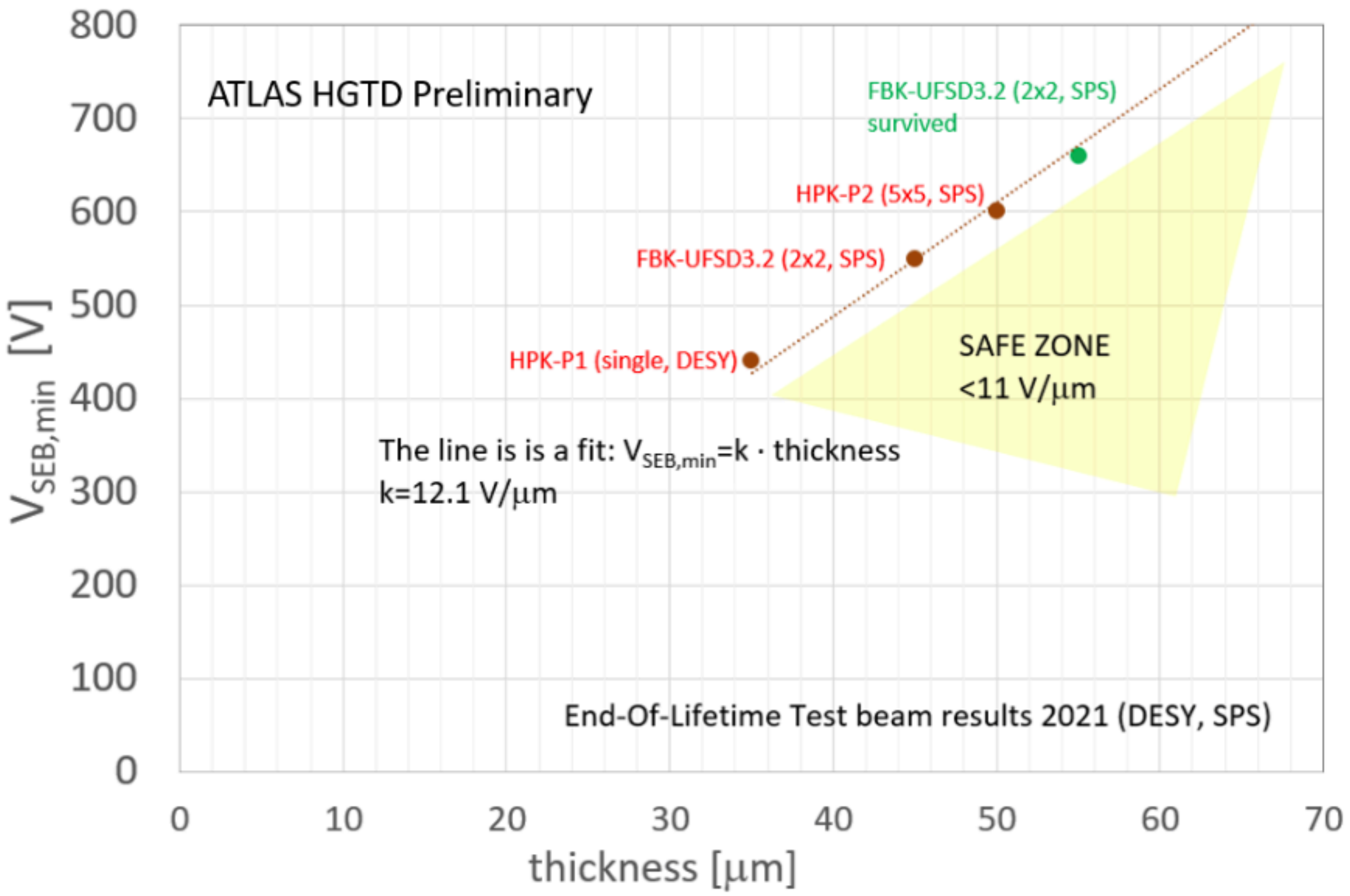
Caused in particle beam by rare events with massive charge deposition (10s MeV)

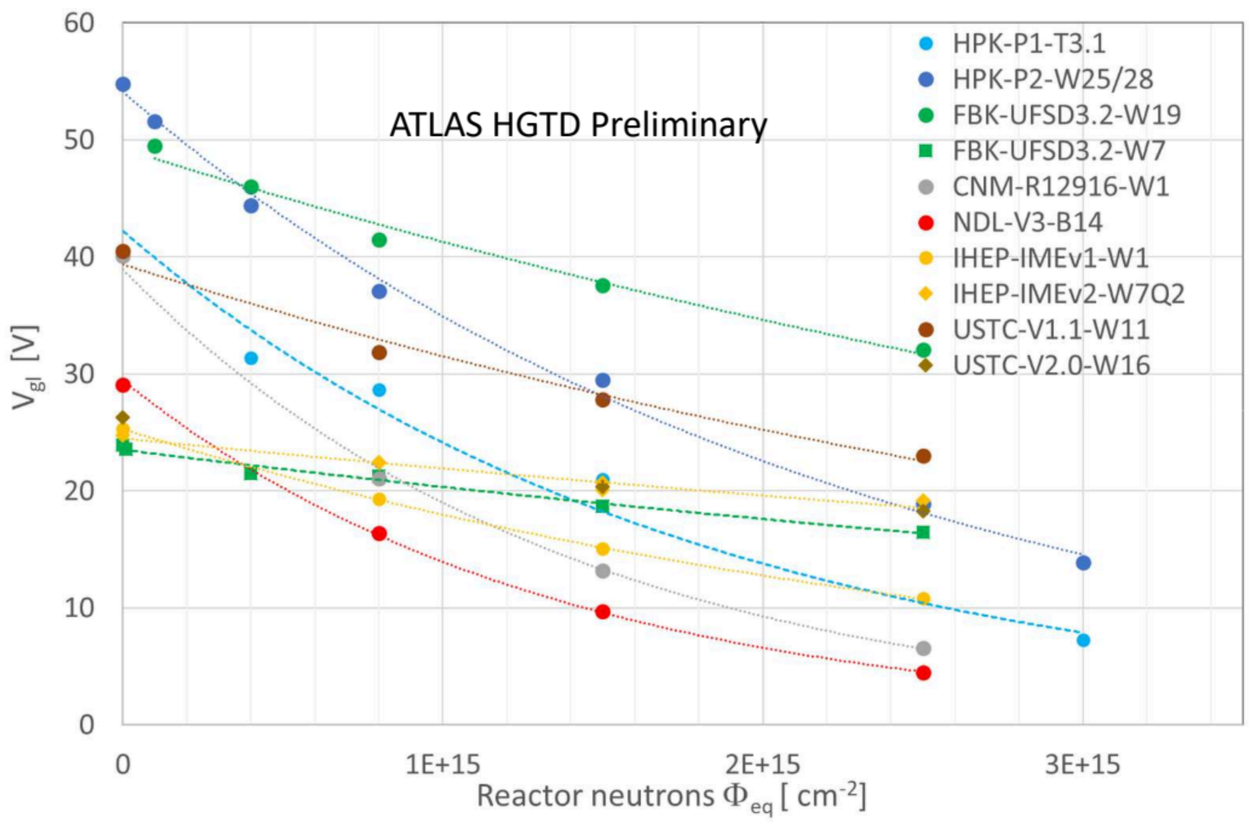
Localized destructive electrical breakdown, “crater”
- Threshold at average electric field in LGAD exceeding **11 V/μm** (550 V for 50 μm thick devices)
- “Natural limit” for LGAD radiation hardness

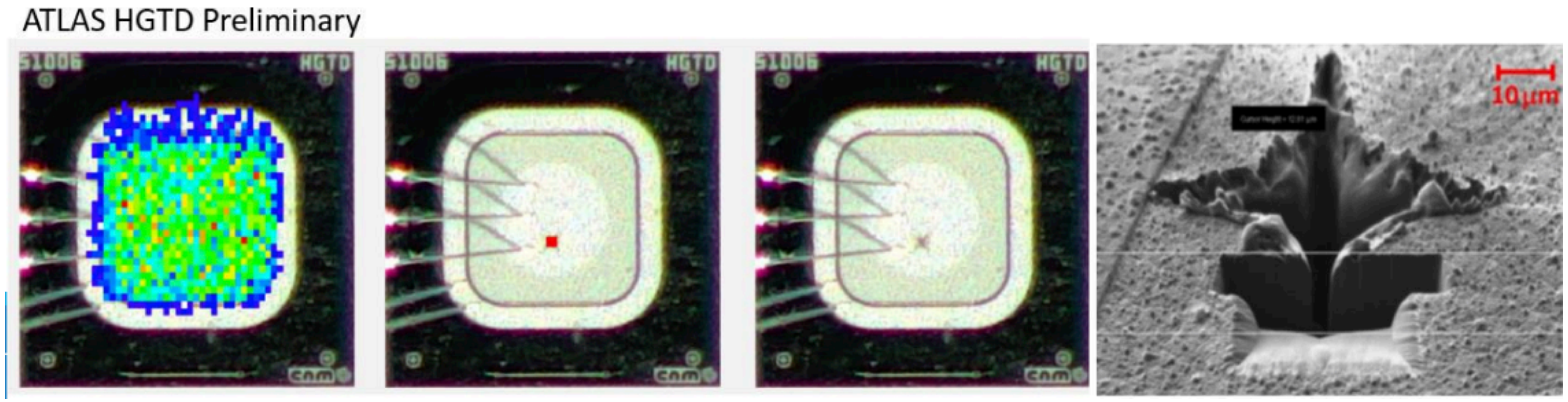
Cannot further increase bias voltage to mitigate gain loss due to radiation damage

Determine the safe operating voltage that these sensors can withstand
Common effort ATLAS/CMS/RD50

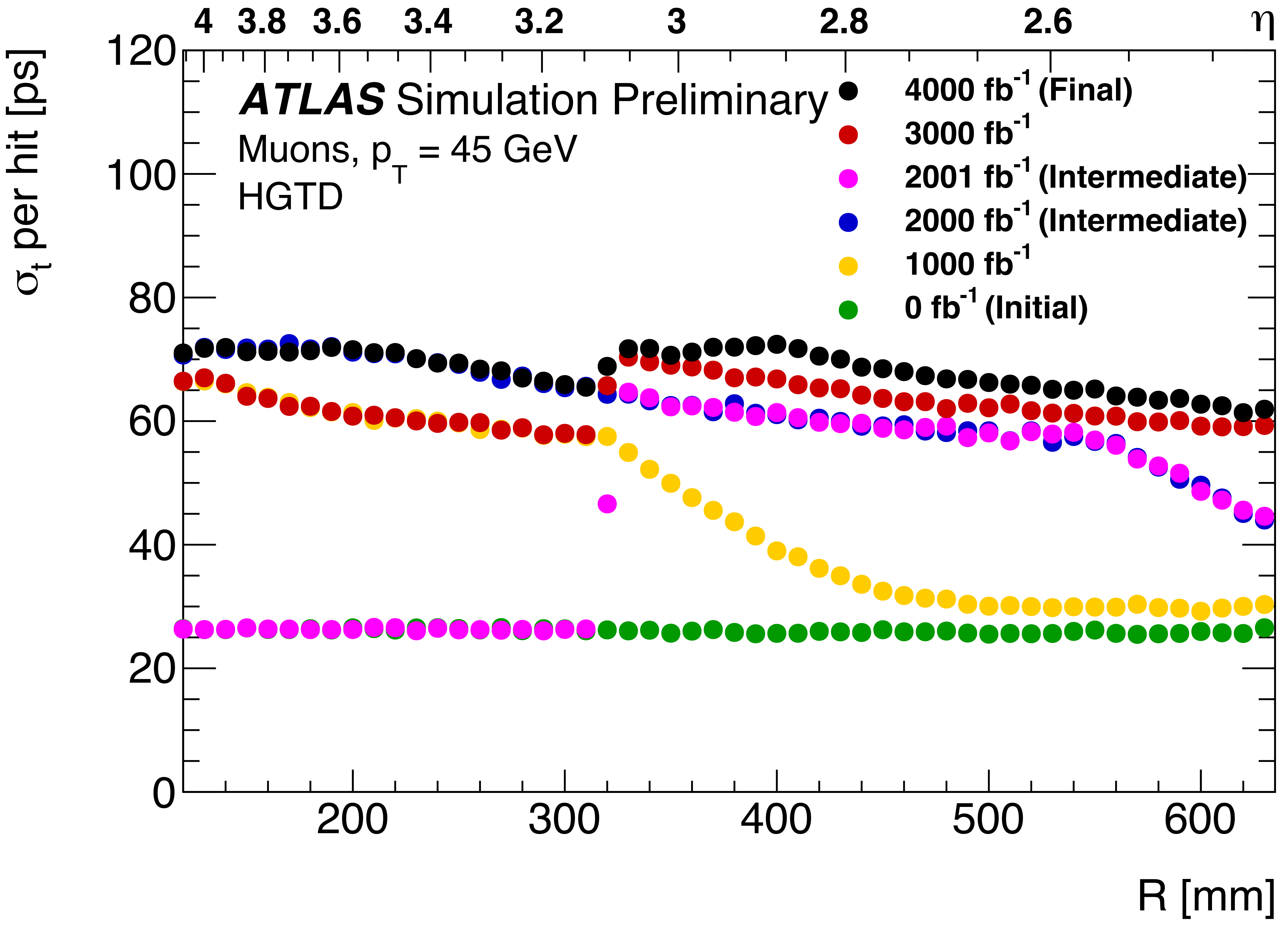
↠ Acceptor removal rate lower for carbon implanted sensors, allows save operation!

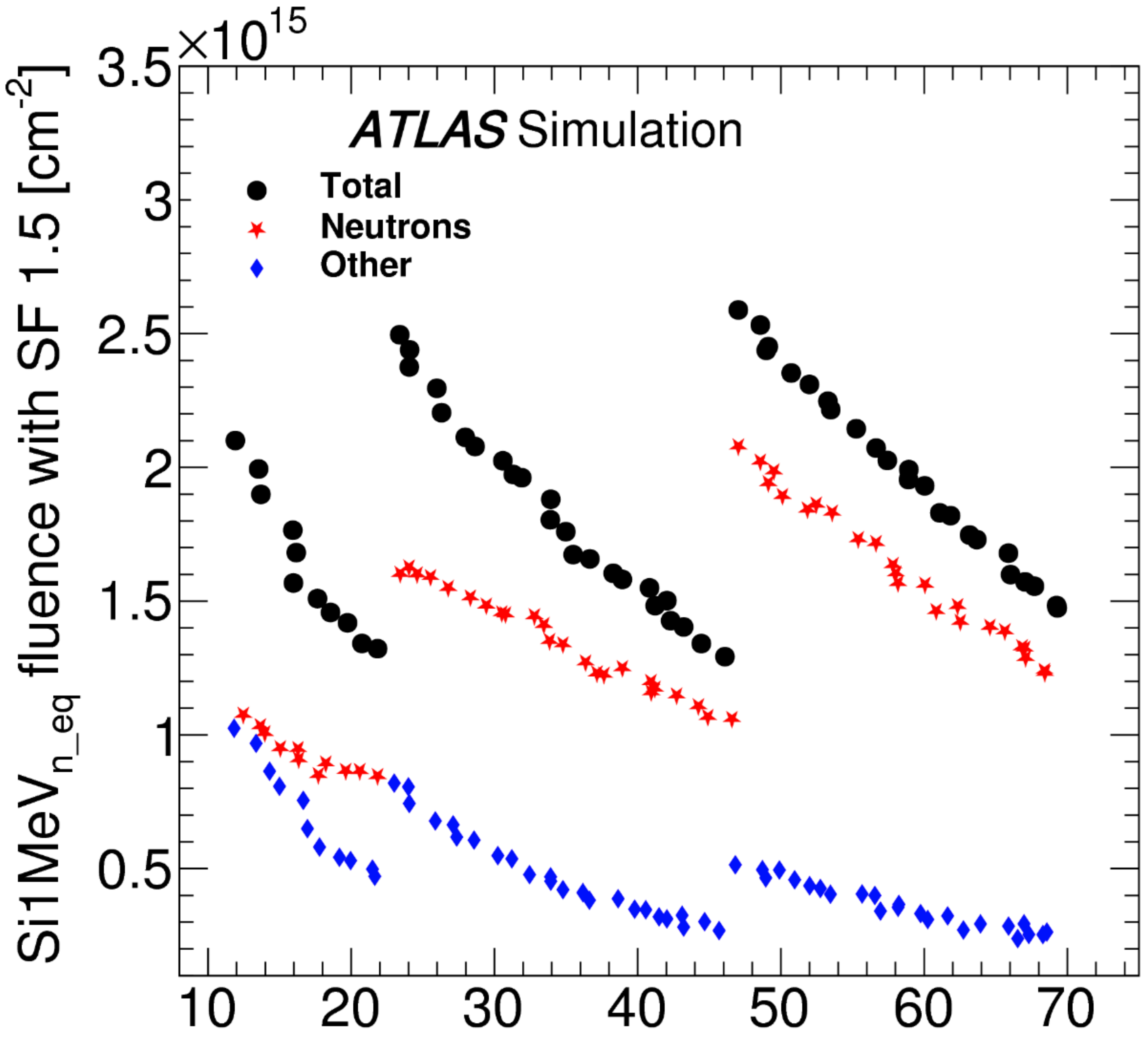




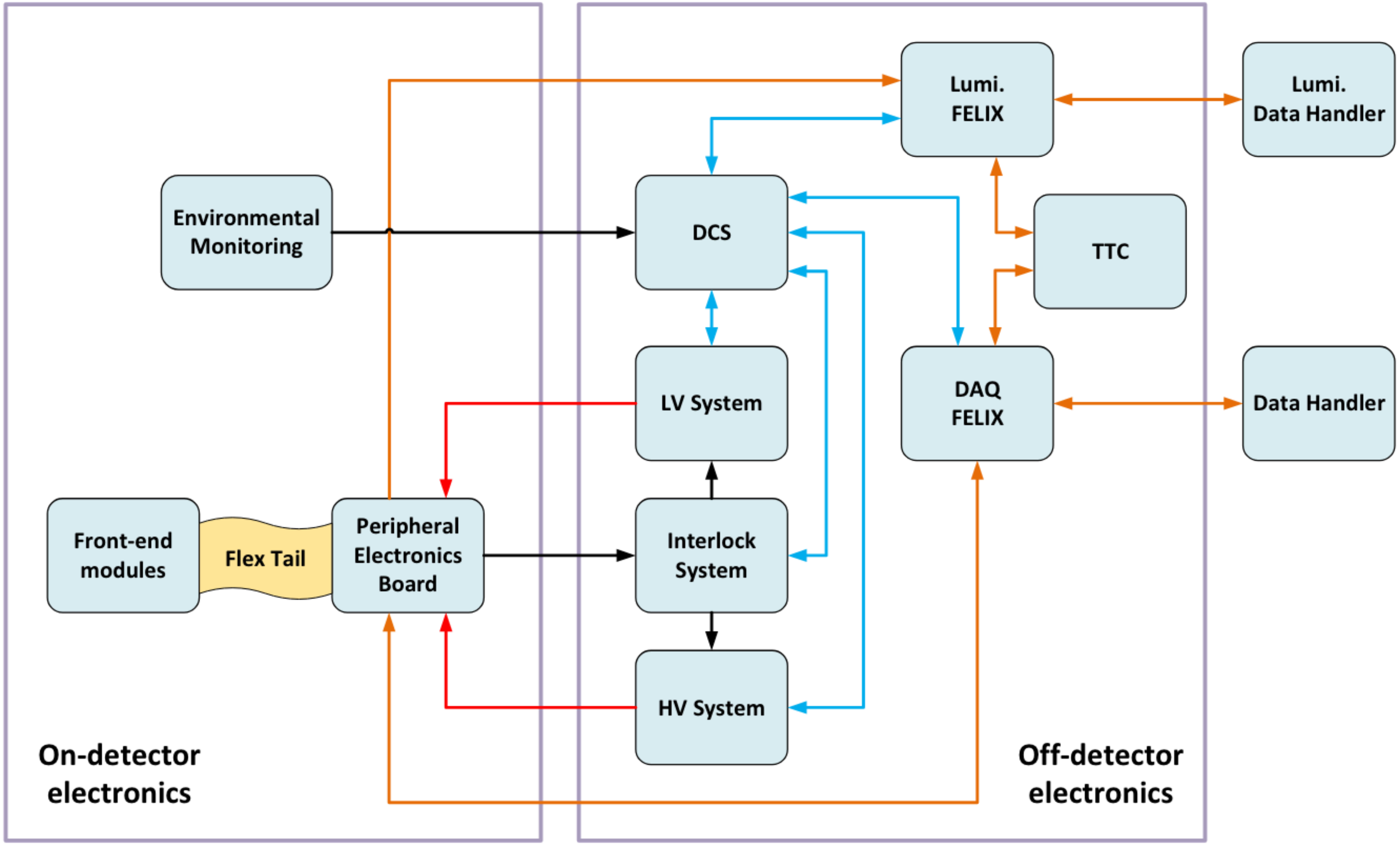


Time resolution (TDR studies)

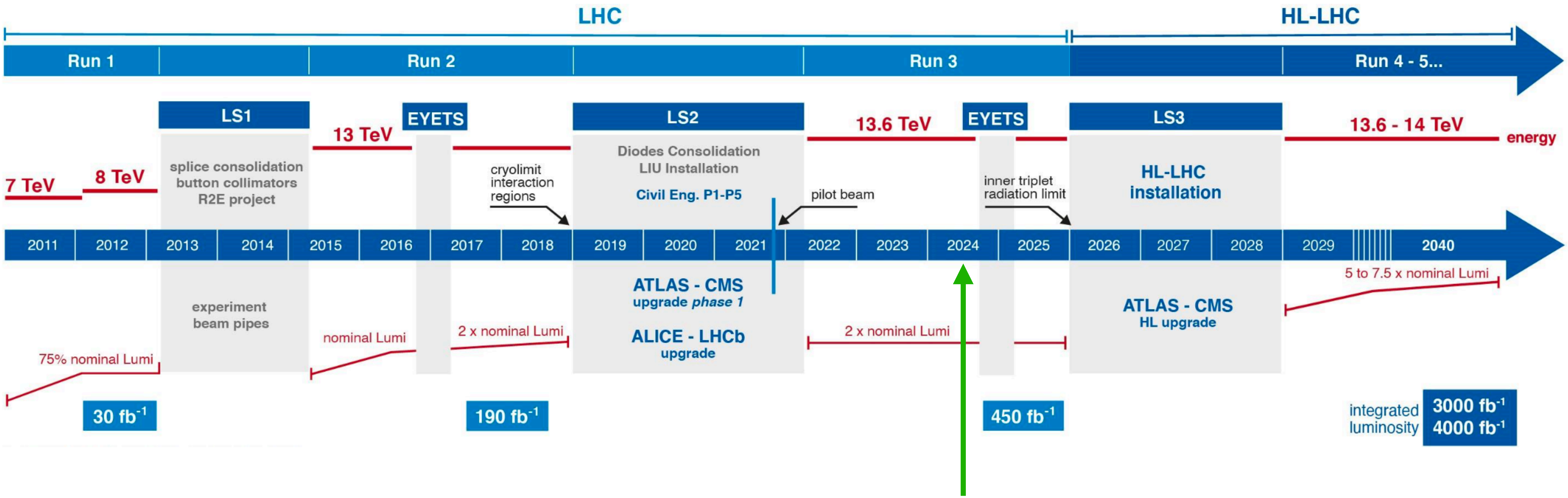




Readout electronics - overview



Schedule



LHC
HL-LHC
Run 1
Run 2
Run 3
Run 4 - 5...
LS1
EYETS
LS2
EYETS
LS3
7 TeV
8 TeV
13 TeV
13.6 TeV
13.6 - 14 TeV
energy
splice consolidation
button collimators
R2E project
cryolimit
interaction
regions
Diodes Consolidation
LIU Installation
Civil Eng. P1-P5
pilot beam
inner triplet
radiation limit
HL-LHC
installation
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2040
5 to 7.5 x nominal Lumi
experiment
beam pipes
ATLAS - CMS
upgrade phase 1
ALICE - LHCb
upgrade
ATLAS - CMS
HL upgrade
75% nominal Lumi
nominal Lumi
2 x nominal Lumi
2 x nominal Lumi
30 fb-1
190 fb-1
450 fb-1
integrated
luminosity
3000 fb-1
4000 fb-1