Testing towards first preproduction ITk Pixel detector units

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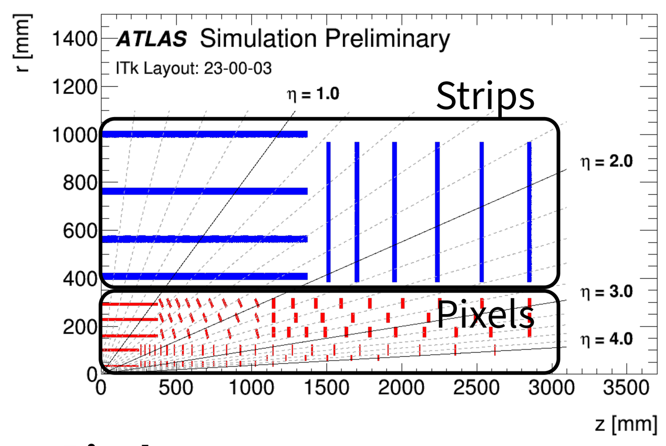
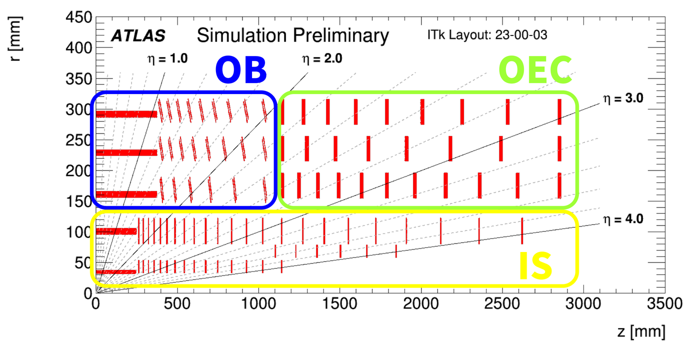
The new ATLAS Inner Tracker (ITk)

ITk Layout

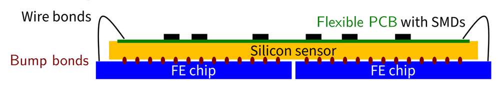
- ITk will fill space of current Inner Detector (ID) with **radius of 1 m** and **length of 6 m**
- replaces current Pixels, Strips and TRT with an **all-silicon tracker**
- divided into Strips and Pixel detector
- extends **tracking coverage** from |η| = 2.5 to 4 (≥ 9 hits / track)



Pixels:

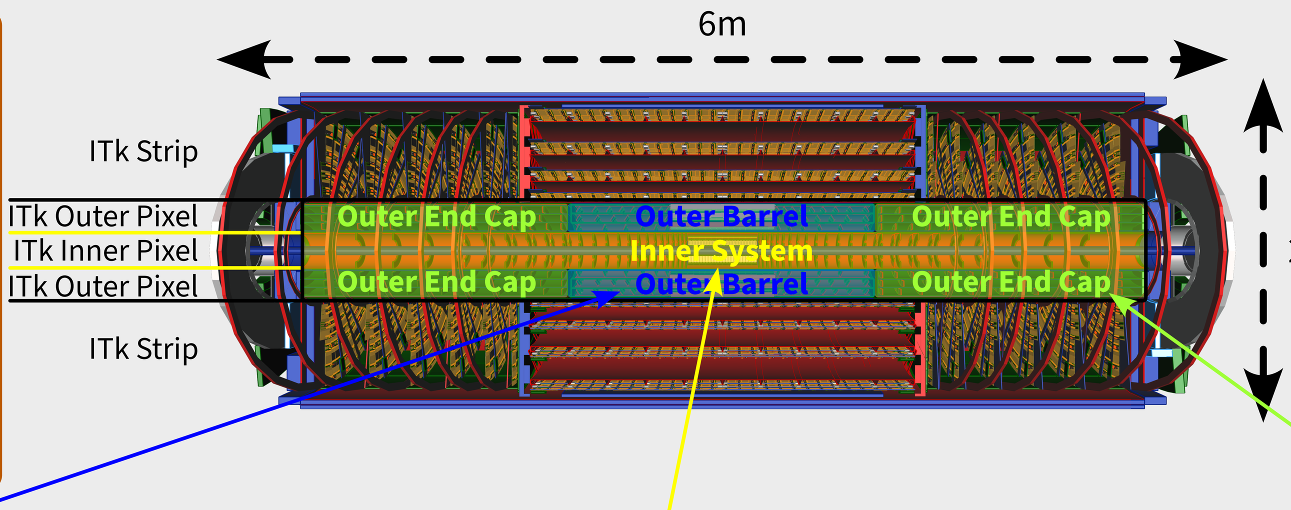


Hybrid Pixel Module

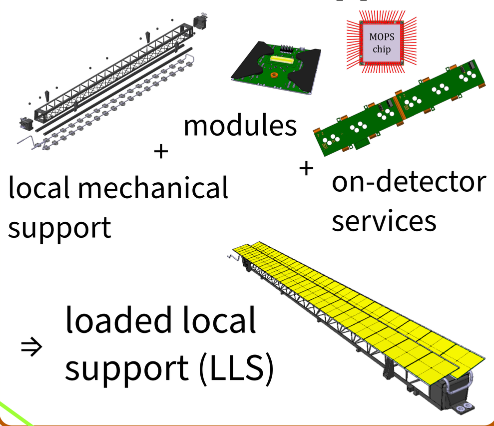


Front End (FE) chip (ITkPix):
- produced in 65 nm CMOS
- SLDO for serial powering

Silicon sensor:
- inner layers: 3D & planar n-in-p
- outer layers: planar n-in-p
- pixels: $25 \times 100\,\mu m^2$, $50 \times 50\,\mu m^2$

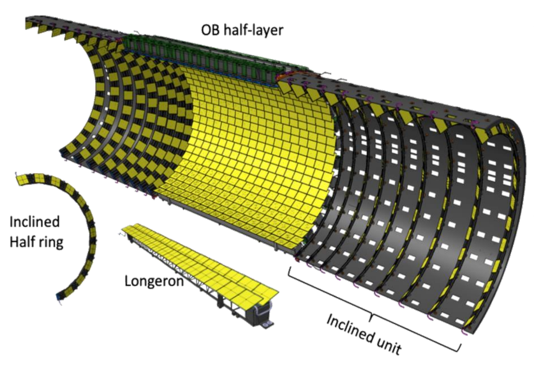


Loaded Local Supports



Outer Barrel (OB)

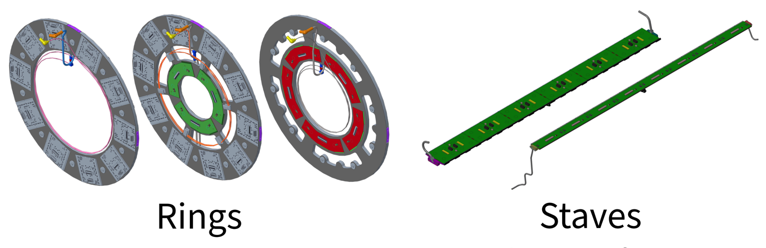
|η| < 2.0



- 4472 pixel modules
- ca. 7 m^2 of active silicon
- 54 % of the total active area in ITk Pixels

Inner System (IS)

|η| < 4.0

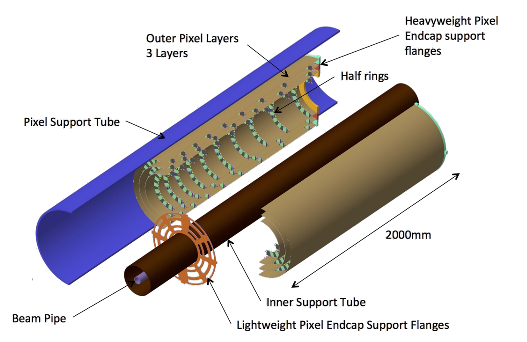


L0: 396 3D pixel modules }
L1: 1160 planar pixel modules } 2.3 m^2 of active silicon

IS designed to be **replaceable** after 2000 fb^{-1}

Outer End Cap (OEC)

2.0 < |η| < 3.6



- 2344 pixel modules
- 3.7 m^2 of active silicon
- 28 % of the total active area in ITk Pixels

Motivation: High-Luminosity (HL)-LHC

Scientific goals:
- Exploring **properties of the Higgs boson** with higher precision
- Searching for **new particles and phenomena** beyond the SM

Operation from 2029 on:
- Proton-proton collisions with up to **14 TeV** center-of-mass energies
- Increase of average collisions per bunch crossing (**pile-up**): $\langle\mu\rangle \sim 60 \Rightarrow \langle\mu\rangle \sim 200$
- Increase of **integrated luminosity** to $\int L\,dt \sim 4000\,fb^{-1}$, an order of magnitude more than current data

⇒ **The ATLAS detector needs to be upgraded**

The ITk Detector Upgrade: Requirements & Summary

- **Radiation hardness** up to $2 \times 10^{16}\,n_{eq}/cm^2$ in innermost layers
- High **track reconstruction efficiency** (μ: > 99%; e, π: > 85%)
- High **granularity**: occupancy < 1%
- High trigger rate of 1 MHz (from previous 100 kHz)
- High **output bandwith** of up to 5.12 Gb/s per Front End chip
- Low **material budget**: $< 1\,X_0$ (radiation length) up to |η| < 2.7
  ⇒ achieved through carbon fibre structures, **serial powering**, thin-walled titanium pipes for CO_2 cooling and data merging

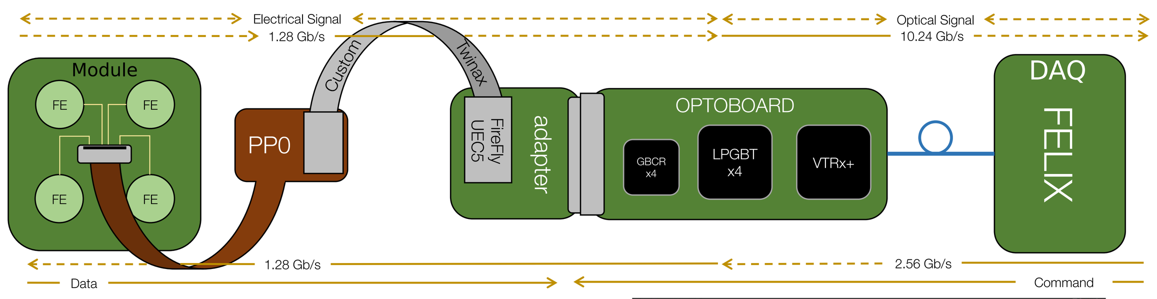
Summary

ITk (ID)	Area (in m²)	# Modules	# Channels (in M)	Pseudorapidity |η|	Instantaneous luminosity L	Integrated luminosity ∫L dt
Pixels	~13 (1.9) ↗ x6.8	~8400 (2000) ↗ x4.2	~5100 (92) ↗ x55	<4 (<2.5) ↗ x1.6	$7 \times 10^{34}\,cm^{-2}s^{-1}$ ($1 \times 10^{34}\,cm^{-2}s^{-1}$) ↗ x7	4000 fb^{-1} (300 fb^{-1}) ↗ x13
Strips	~165 (61) ↗ x2.7	~9700 (4088) ↗ x4.4	~60 (6.3) ↗ x9.5			

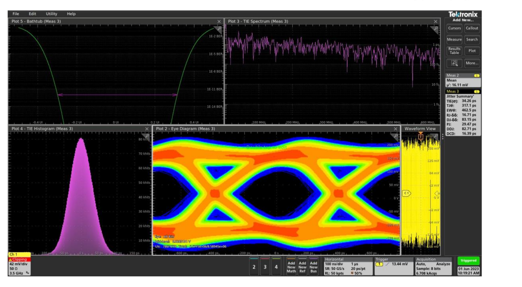
ITk Pixel System Test

Goal: **Design validation and tests of interplay between components**
- Demonstrate that detector units fulfill detector requirements consistently
- Validate different loading procedures and establish their equivalence
- Define approach for Quality Control during production

Data Transmission

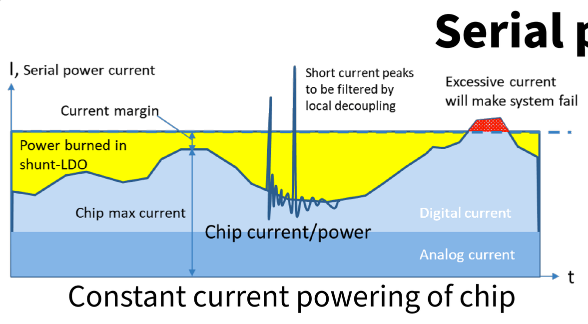


- Gigabit receiver chip (GBCR): equalizer
- low-power Gigabit transceiver (**lpGBT**)
- VTRx+: electrical/optical transceiver
- each FE has 4 x 1.28 Gbit/s electrical links
- module can do 4→1 or 2→1 **data merging**
- DAQ uses Front-End Link eXchange (FELIX)



Eye diagram with real services

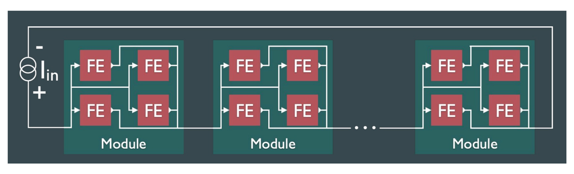
Serial powering



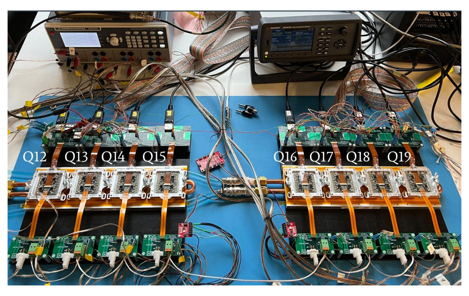
Constant current powering of chip

- FE chips have **Shunt Low Drop Output** (**SLDO**) power regulators
- SLDO's dynamically adjust shunt current to have constant local voltages on chip when powered with **constant current**

⇒ **reduces material budget** of detector due to less cabling



Serial powering (SP) chain of modules



SP chain test with ITkPix modules

Orchestration

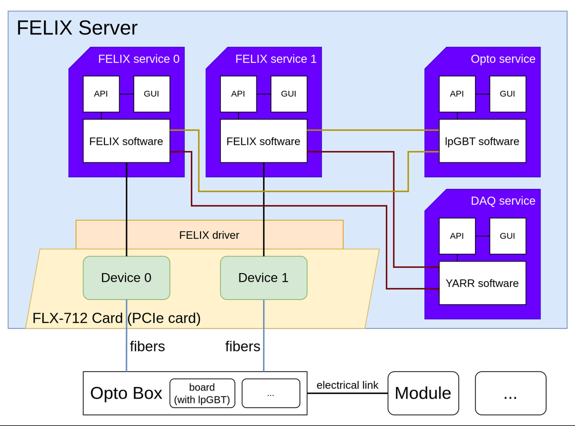
- Framework based on distributed microservices
- (Command-line) software packaged with configuration files in **immutable docker containers**
- Communication via **REST API**
- Services also provide a GUI

⇒ operation of setup through **uniform interface**

docker

GUI of the **FELIX microservice**

Microservice framework for **online software** packages



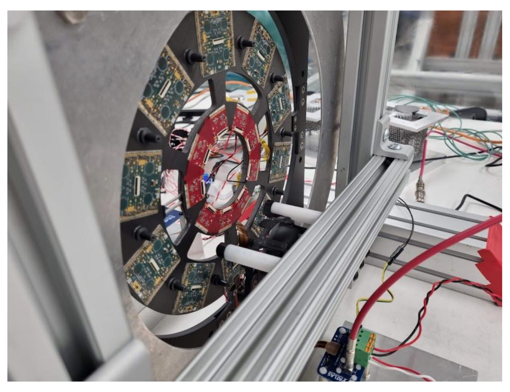
RD53A programme

All loaded local support types of all subsystems were tested.

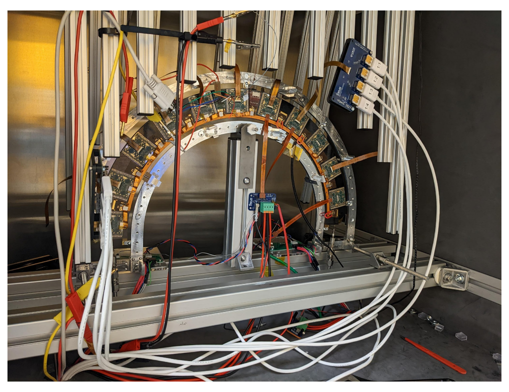
⇒ **first opportunity** to test a complete detector system

Test setups:
- using the **RD53A** FE prototype (3 different analog front-ends and no data merging)
- in environmental box with monitoring of T, dew point, light
- with **interlock** to ensure T on modules < 40 °C and dew point < -60 °C

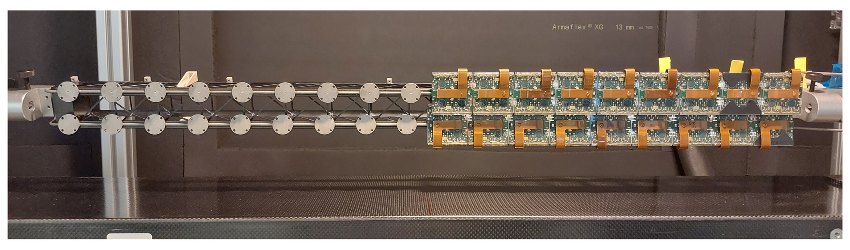
Goal: test RD53A modules after loading and after thermal cycling



Coupled-ring from IS

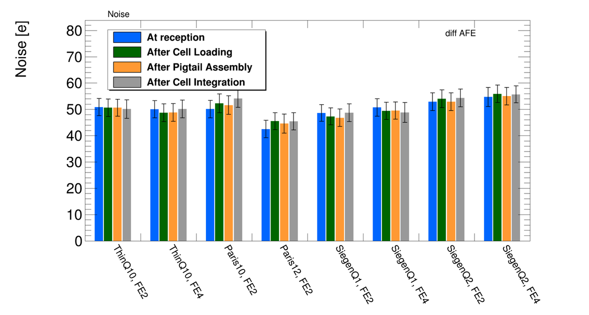


Half-ring from OEC



Longeron from OB loaded with modules in two SP chains

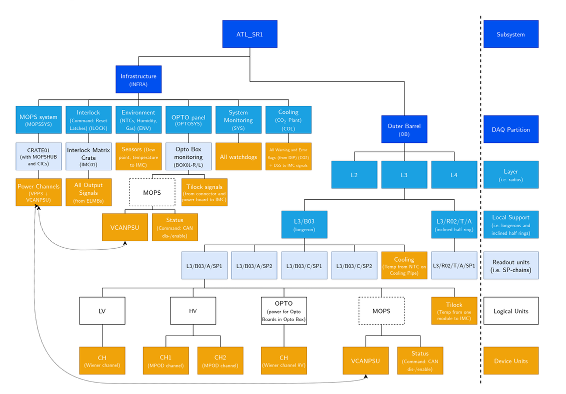
Electrical test results before and after loading of RD53A modules validate the loading procedure

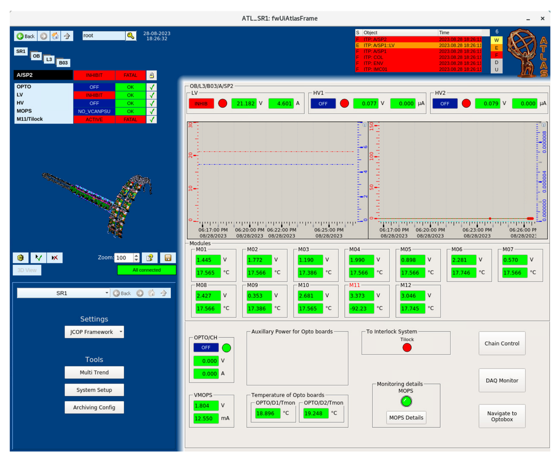


Detector Control System (DCS)

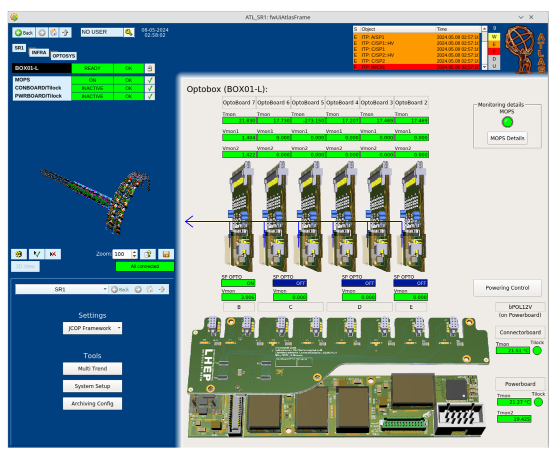
Scalable and configurable DCS for large scale multi-module detector assemblies

Finite State Machine provides high-level control mechanism as foreseen during detector operation





SP chain control and monitoring

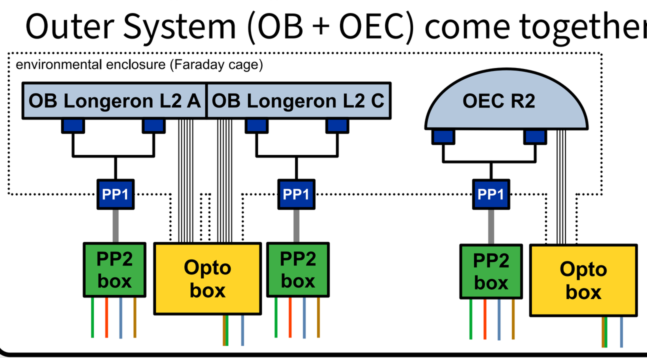


Opto box monitoring

⇒ All tests **successfully finished**, which allowed the project to move to preproduction of loaded local supports

Outlook: ITk Pixel Slice Test

Plan: beginning of 2025, preproduction **detector units** of the Outer System (OB + OEC) come together to build a detector slice



With a successful slice test, the collaboration can **start the production** of the pixel detector units.

ITk Pixel detector units production

QC Tests

Quality control (QC) ensures quality of each produced component during ongoing production.

Electrical QC procedures of loaded local supports:

(from lessons learned in System Test)
- Connectivity and readback check of interlock module and MOPS chip
- Data transmission path check using Bit Error Rate Test
- **Module performance tests:**
  - I(V) scan of the sensors bias voltage
  - FE scans: digital, analog, threshold and disconnected bump bonds
- Low power mode test of modules

⇒ Results are uploaded into a **production database**

Preproduction

- **currently ongoing**
- first system-level tests expected in September 2024
- successfully tested preproduction units go into slice test

References

- Expected Tracking and Related Performance with the Updated ATLAS Inner Tracker Layout at the High-Luminosity LHC, ATL-PHYS-PUB-2021-024, CERN, 2021.
- ATLAS Inner Tracker Pixel Detector: Technical Design Report, CERN-LHCC-2017-021, CERN, 2017.