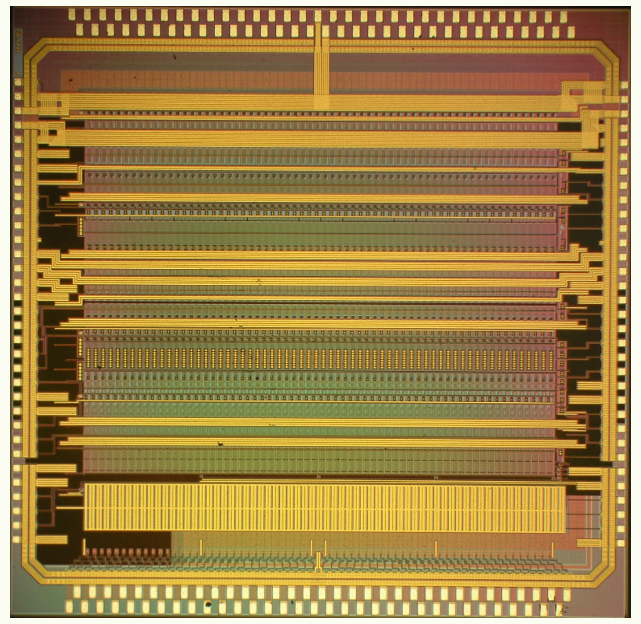
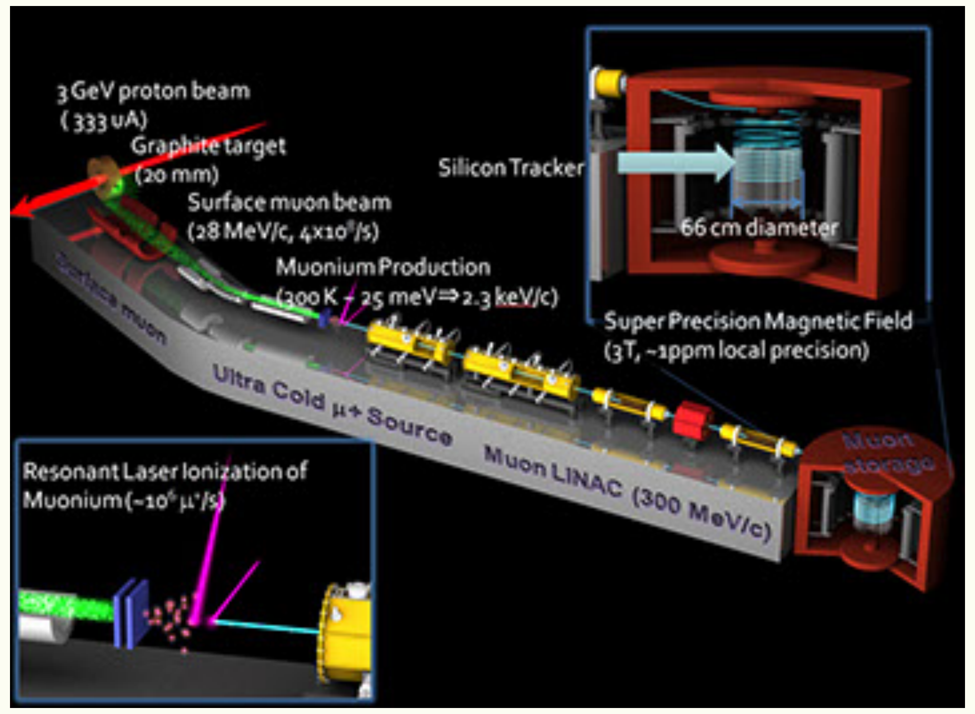
Studies for the Phase-2 ATLAS ITk pixel upgrade

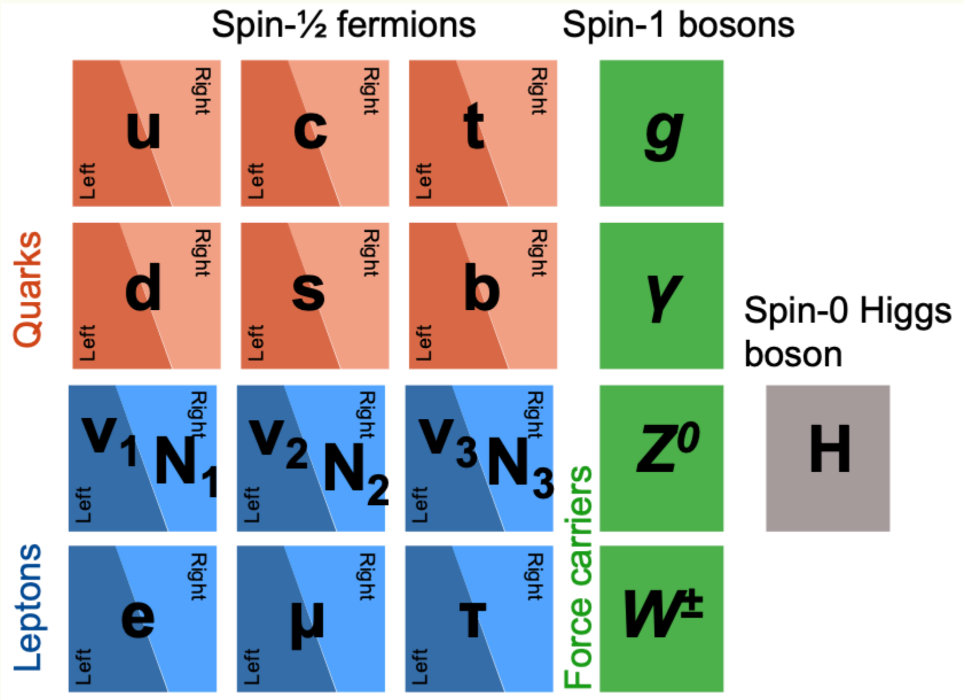
Shohei Shirabe

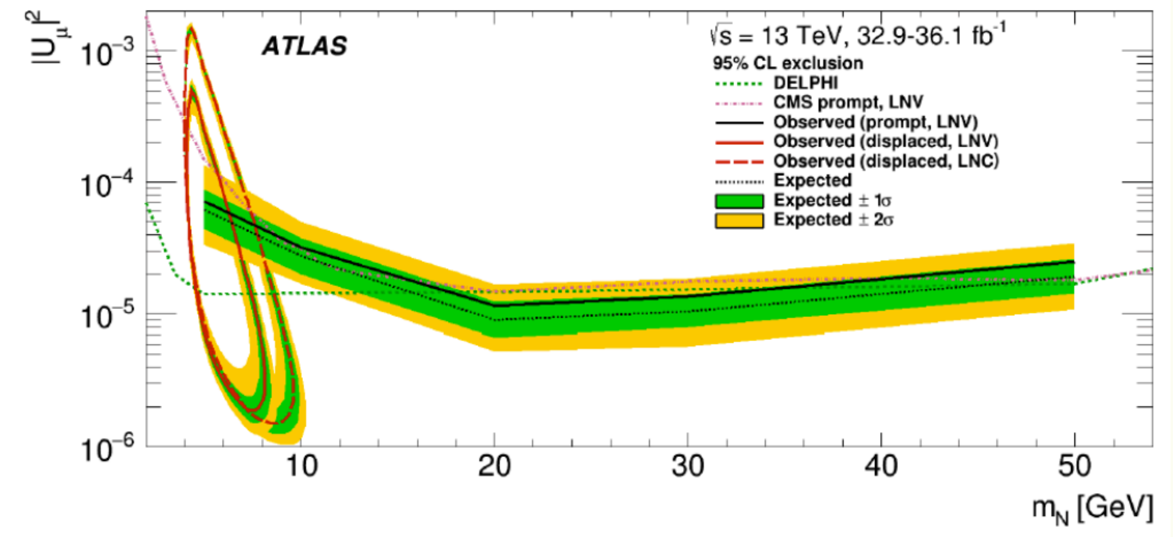
Brief self-introduction

- Kyushu University
  - Summer 2013: MEG Experiment @ PSI
  - 2013-2014: muon g-2/EDM Experiment @ J-PARC
  - 2015 - : ATLAS @ CERN
    - SCT Operation
    - Displaced heavy neutral lepton analysis
- Tokyo Institute of Technology, University of Geneva
  - 2019 - : ATLAS @ CERN
    - ITk Upgrade
- LPSC
  - 2022 - 2023 : ITk Upgrade



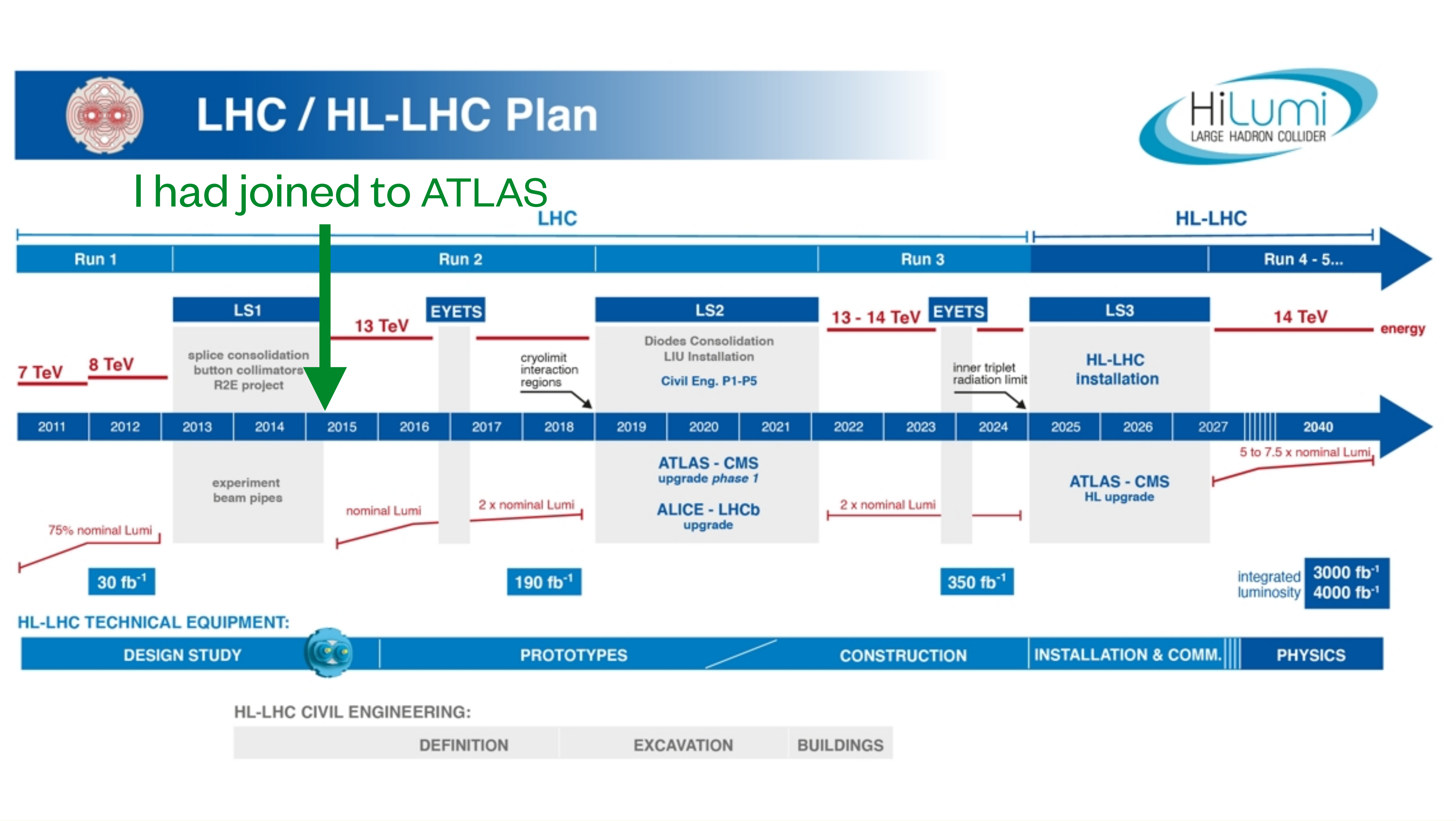


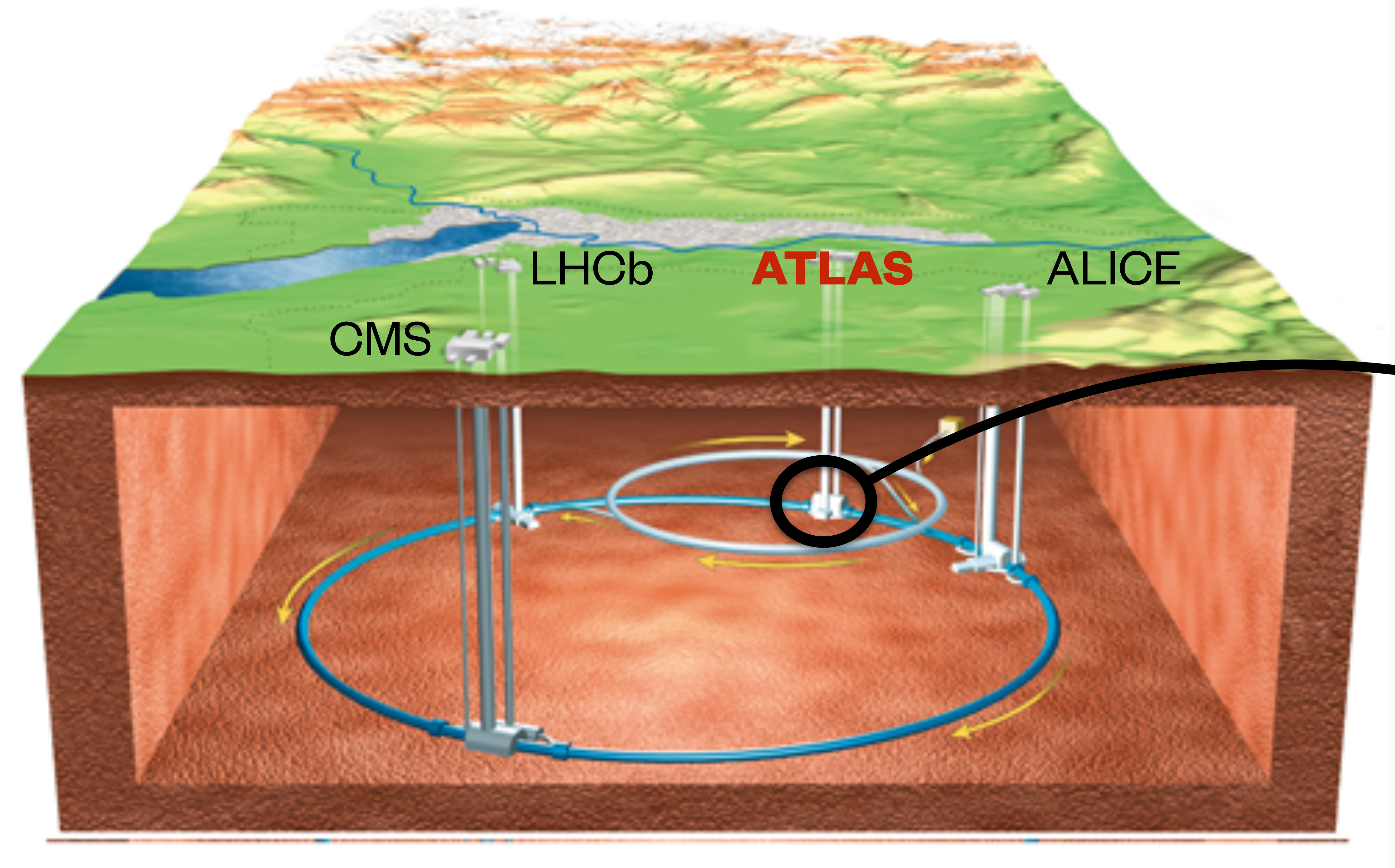


LHC and ATLAS

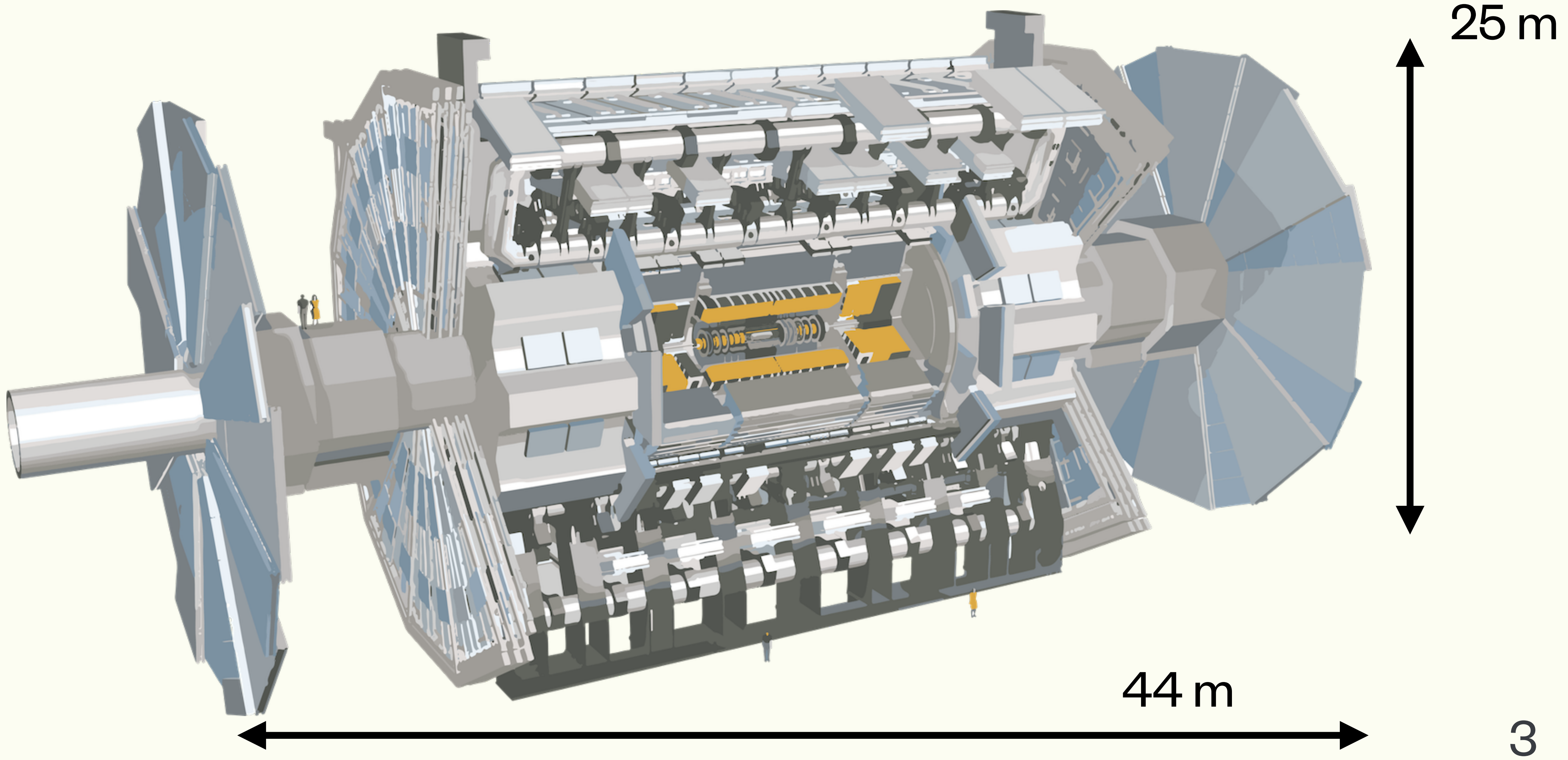
LHC

- 2008 - 2025
- <μ> ~ 30
- $1 \times 10^{34}\ cm^{-2}s^{-1}$
- $400\ fb^{-1}$ ($190\ fb^{-1}$ so far)





ATLAS Detector



LHC and ATLAS

LHC

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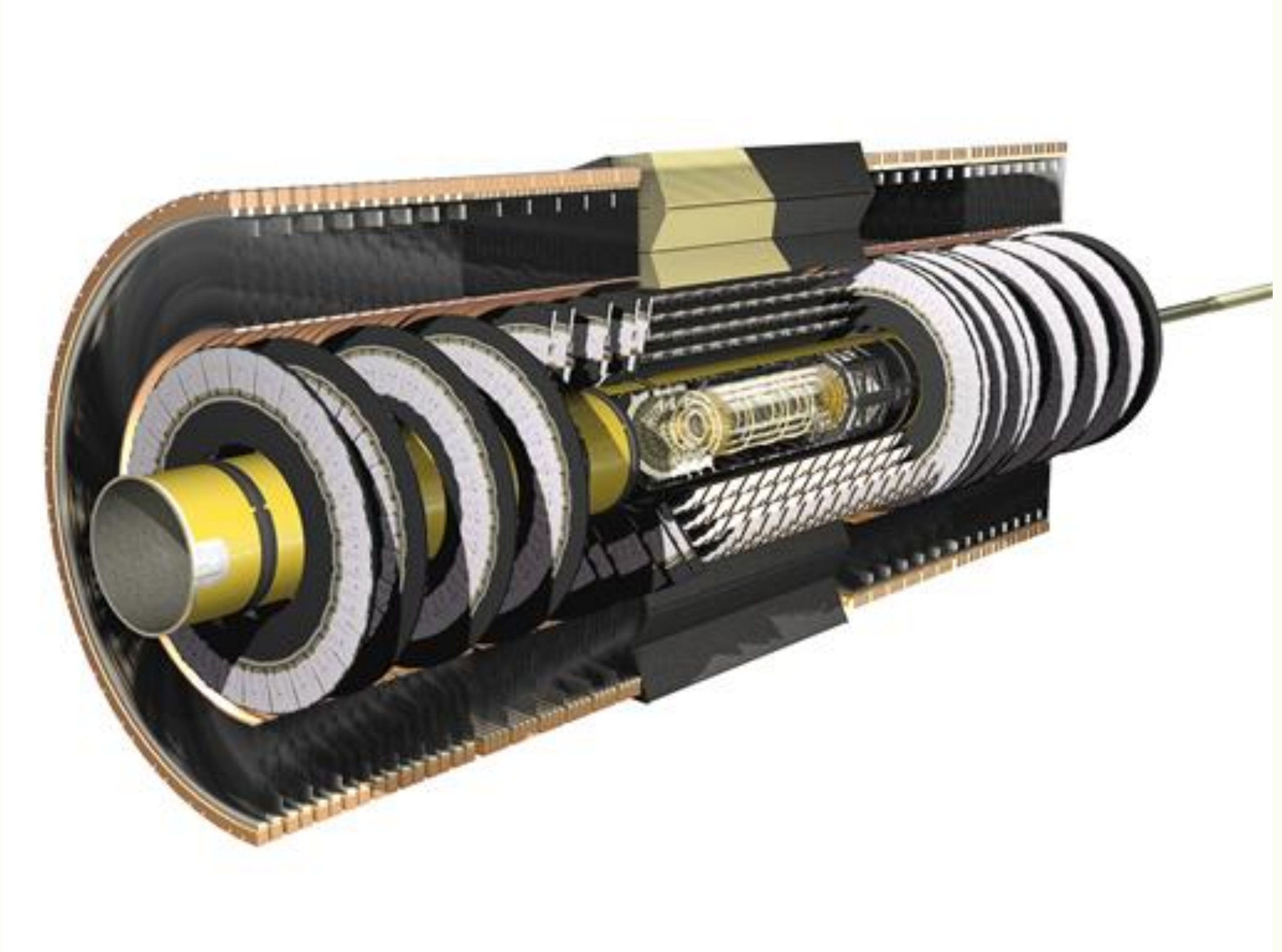
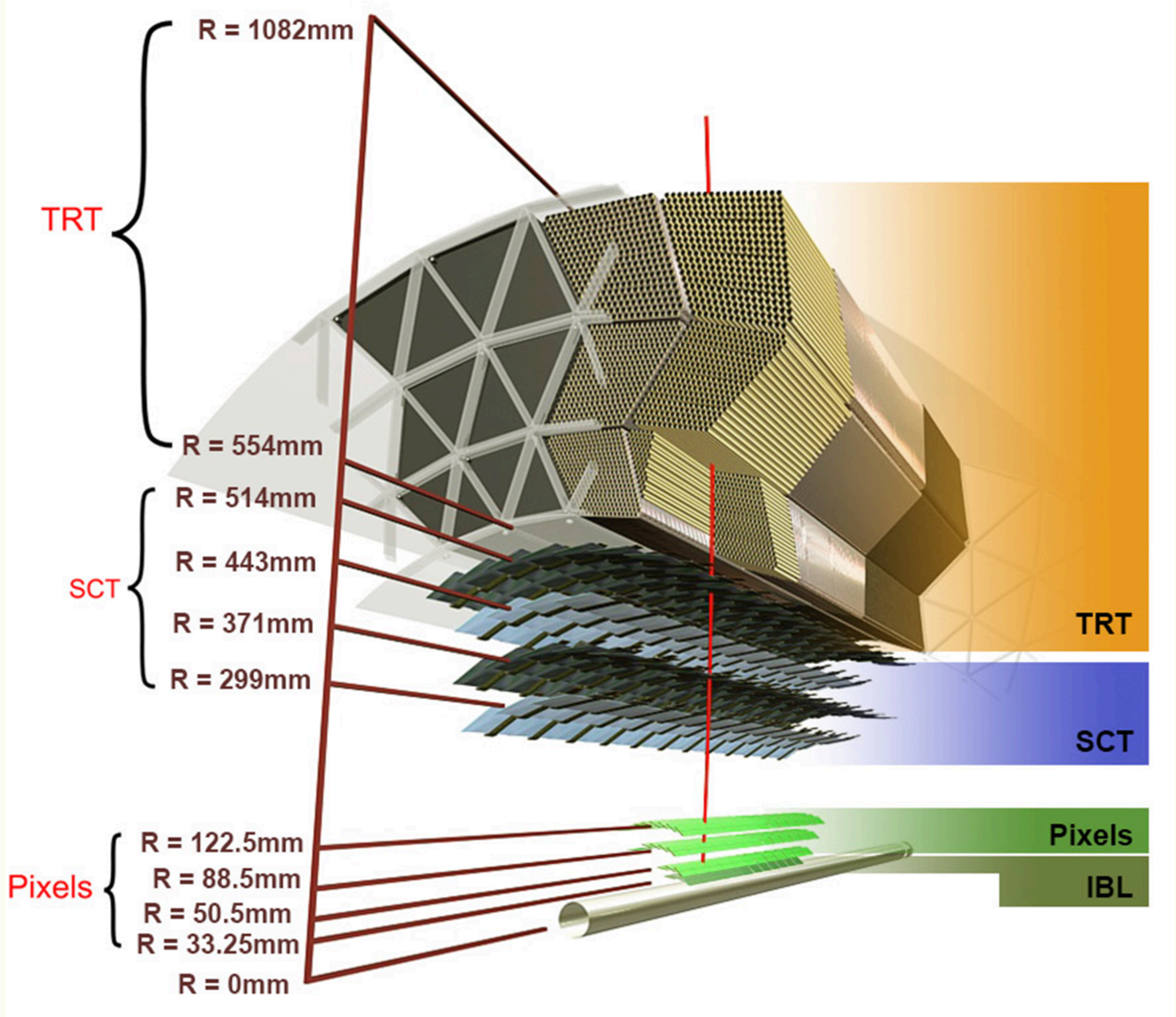
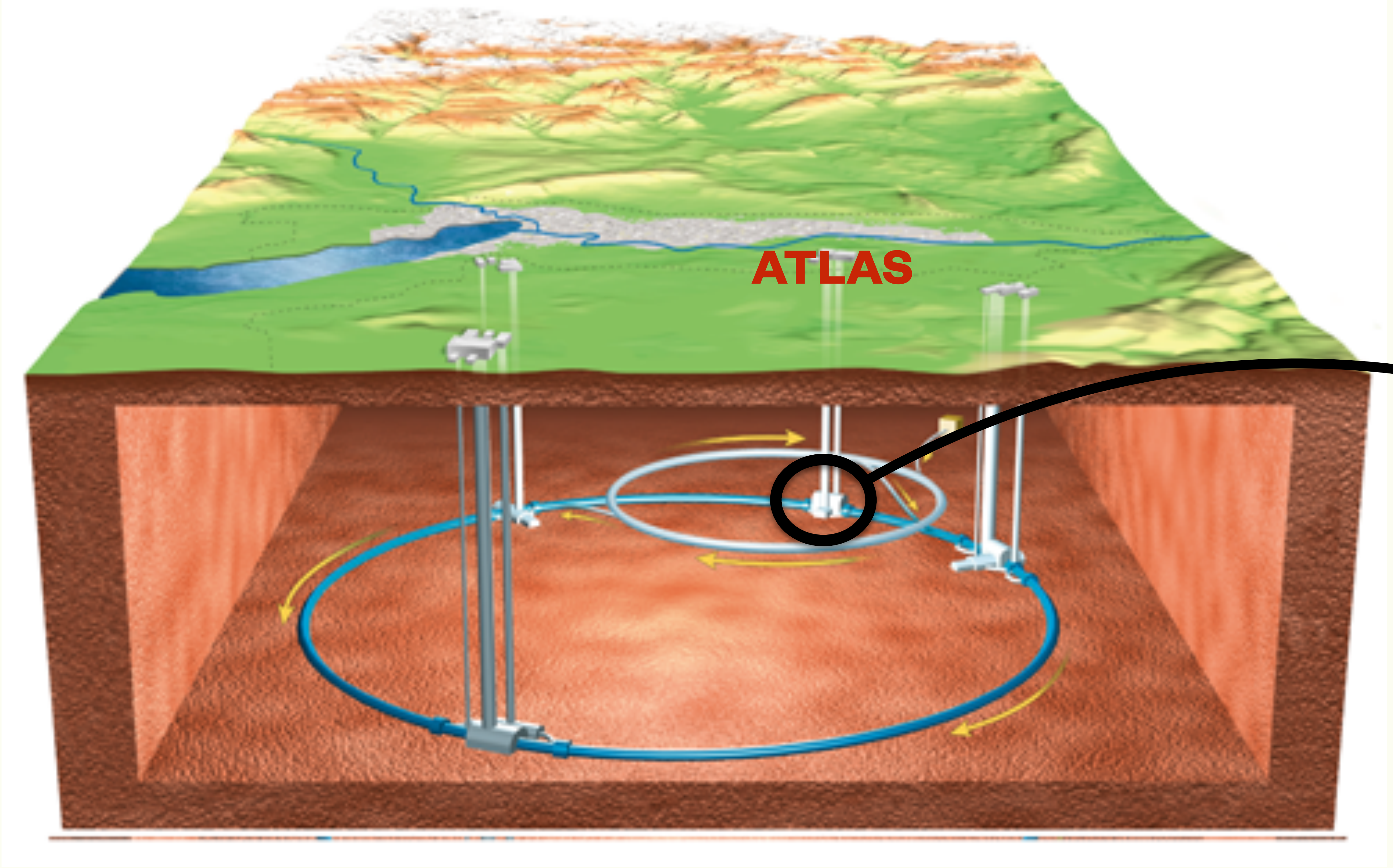
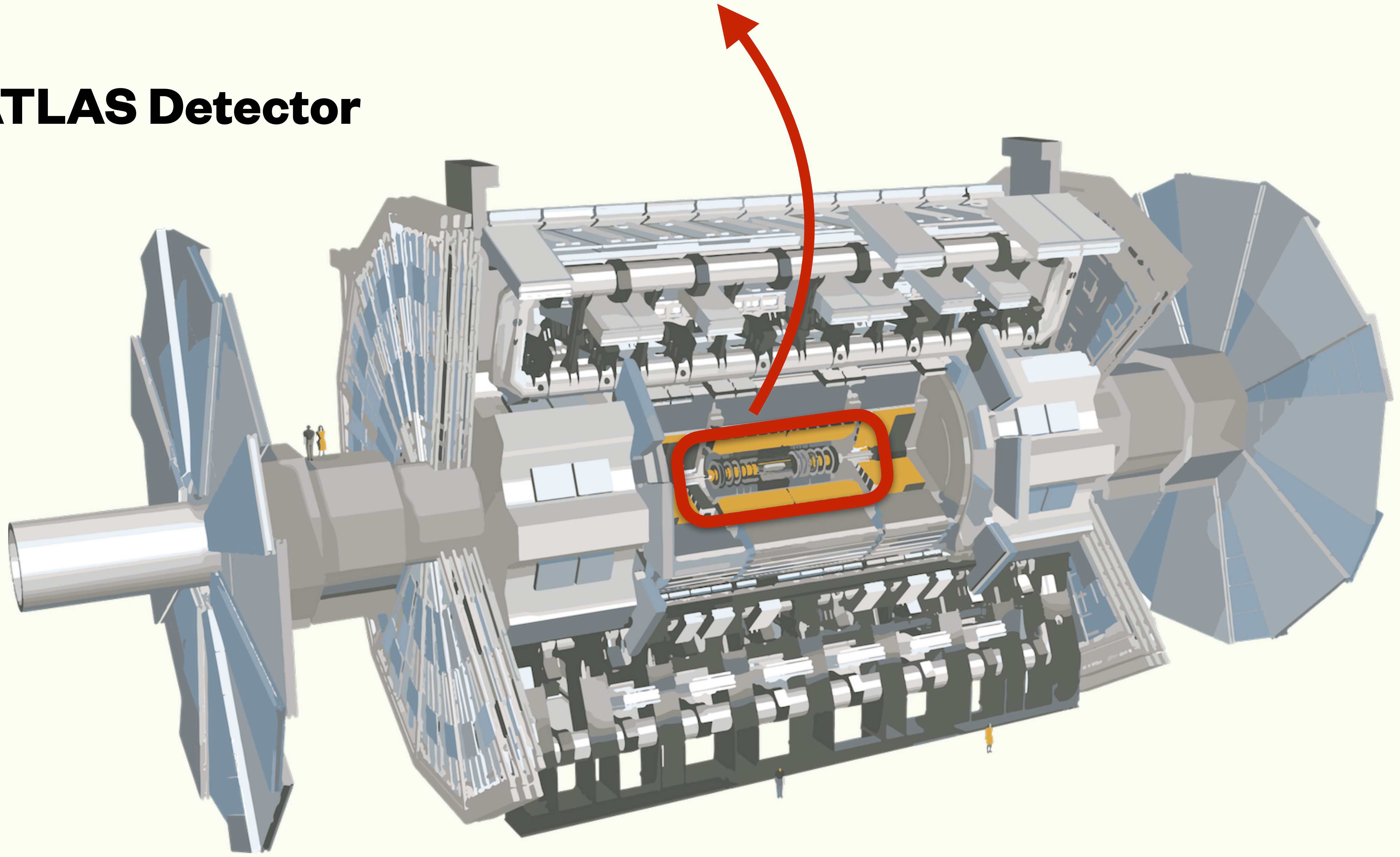
ATLAS "Current" Inner Detector







ATLAS Detector



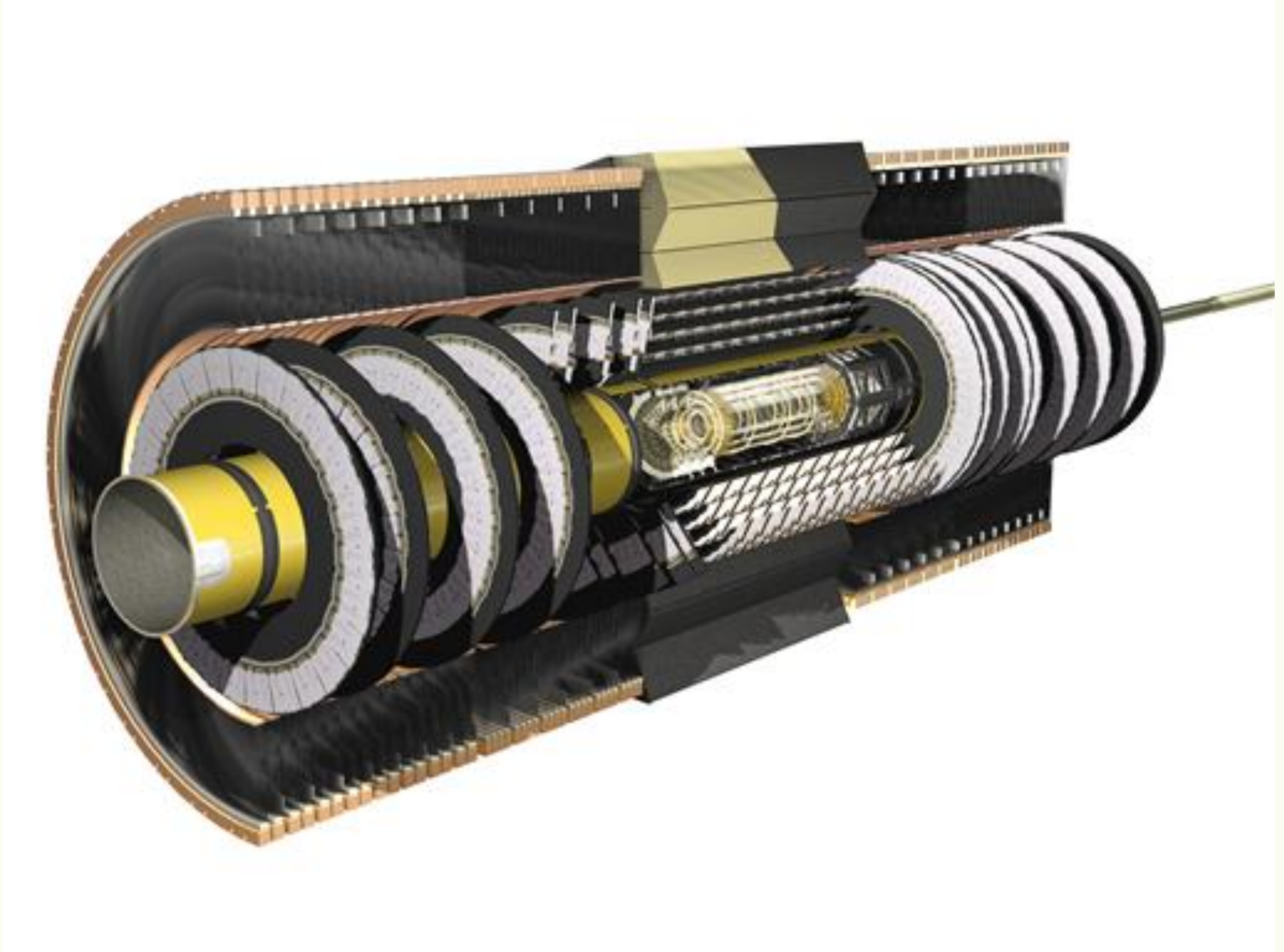
High Luminosity LHC

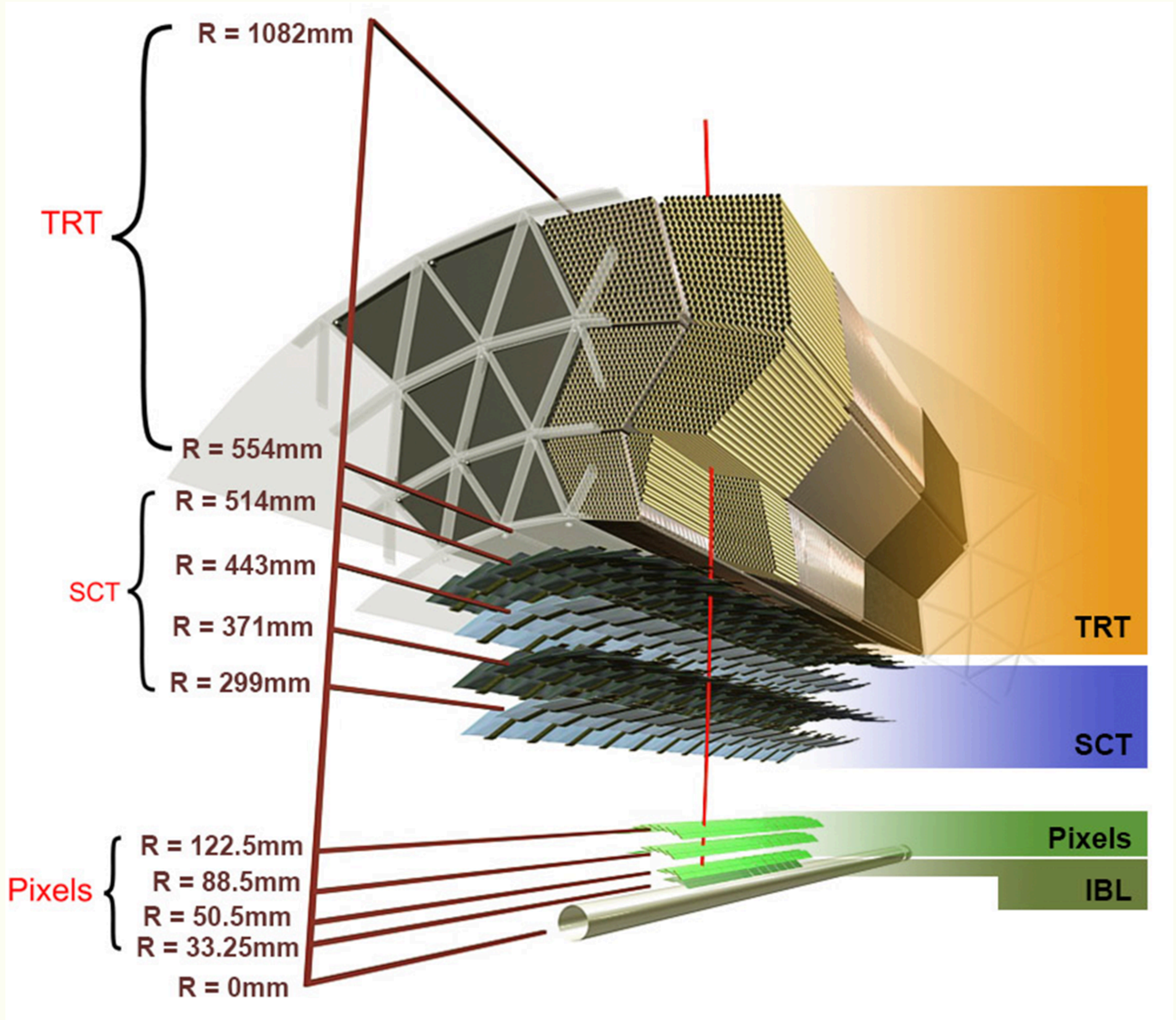
LHC → Upgrade → **HL-LHC**

LHC
- 2008 - 2025
- <μ> ~ 30
- 1 x 10^{34} $cm^{-2}s^{-1}$
- 400 fb^{-1} (190 fb^{-1} so far)

HL-LHC
- 2028 ~
- <μ> ~ 200
- 7.5 x 10^{34} $cm^{-2}s^{-1}$
- 4000 fb^{-1}

ATLAS "Current" Inner Detector





Requirement for the pixel detector and its readout becomes demanding

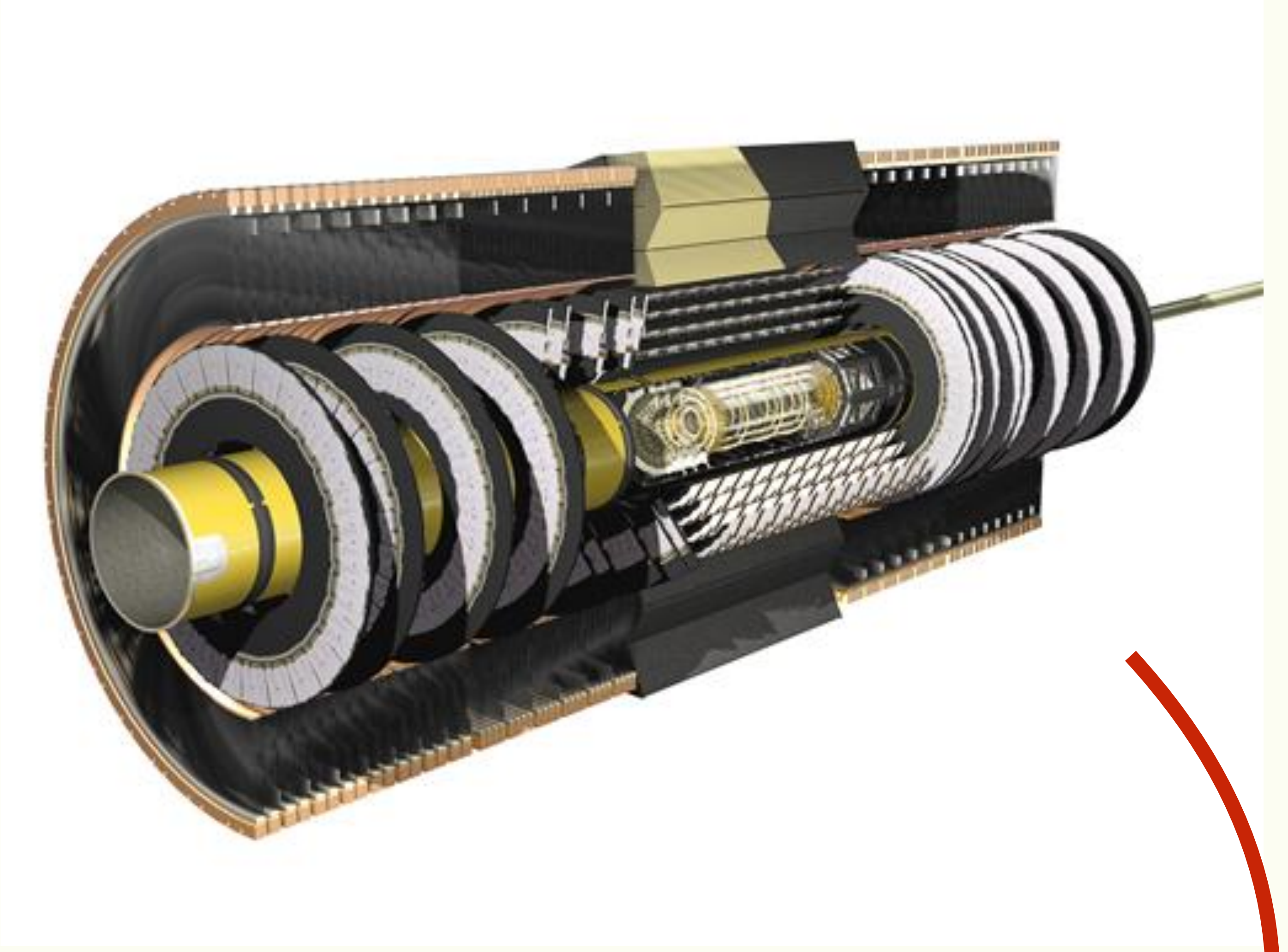
- **Radiation tolerance**
  - Current ID Pixel designed for ~ 400 fb^{-1}
- **Bandwidth saturation**
  - Current ID designed to accommodate <μ> ~ 50 at 2 x 10^{34} cm^{-2} s^{-1}

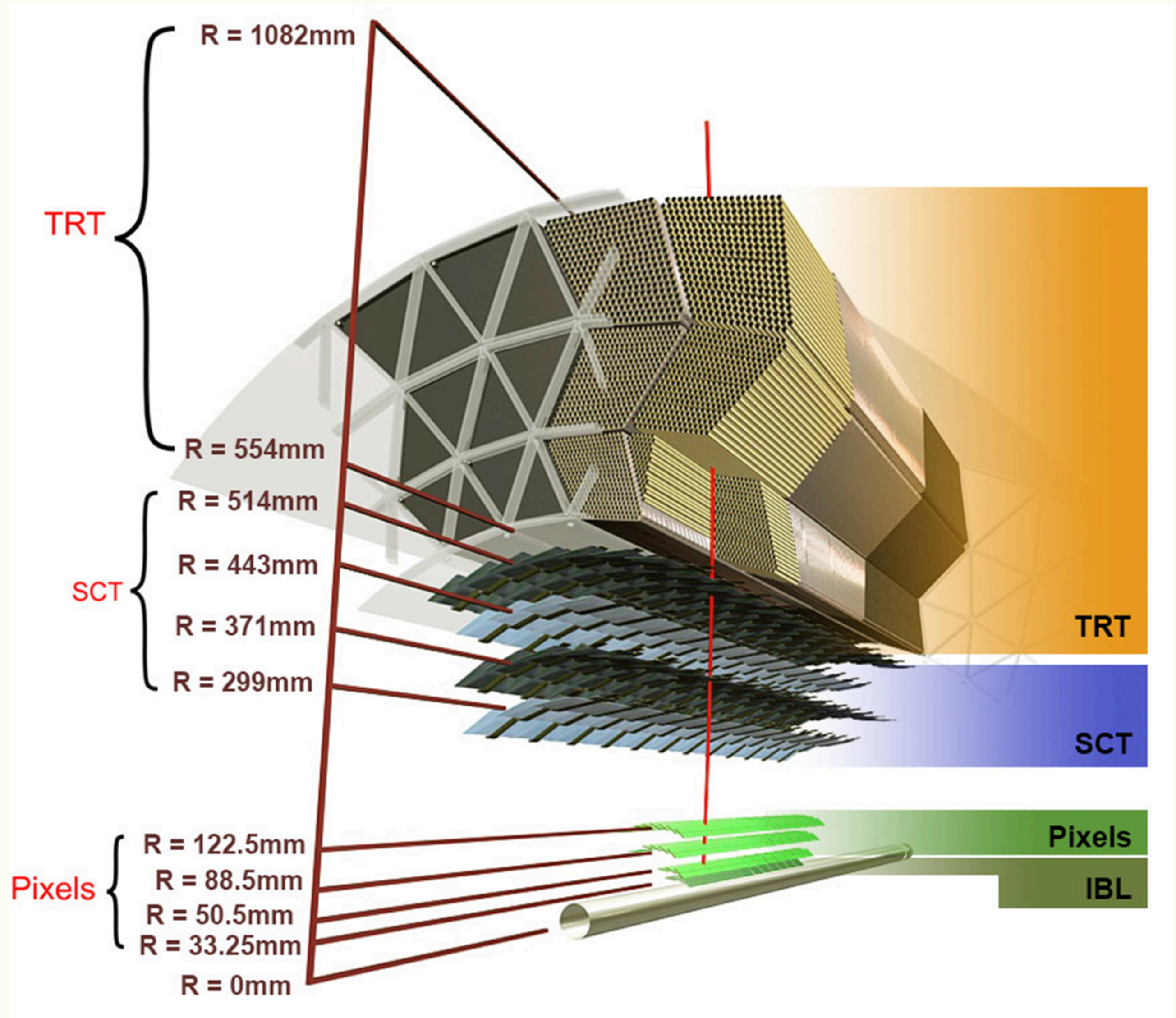
High Luminosity LHC

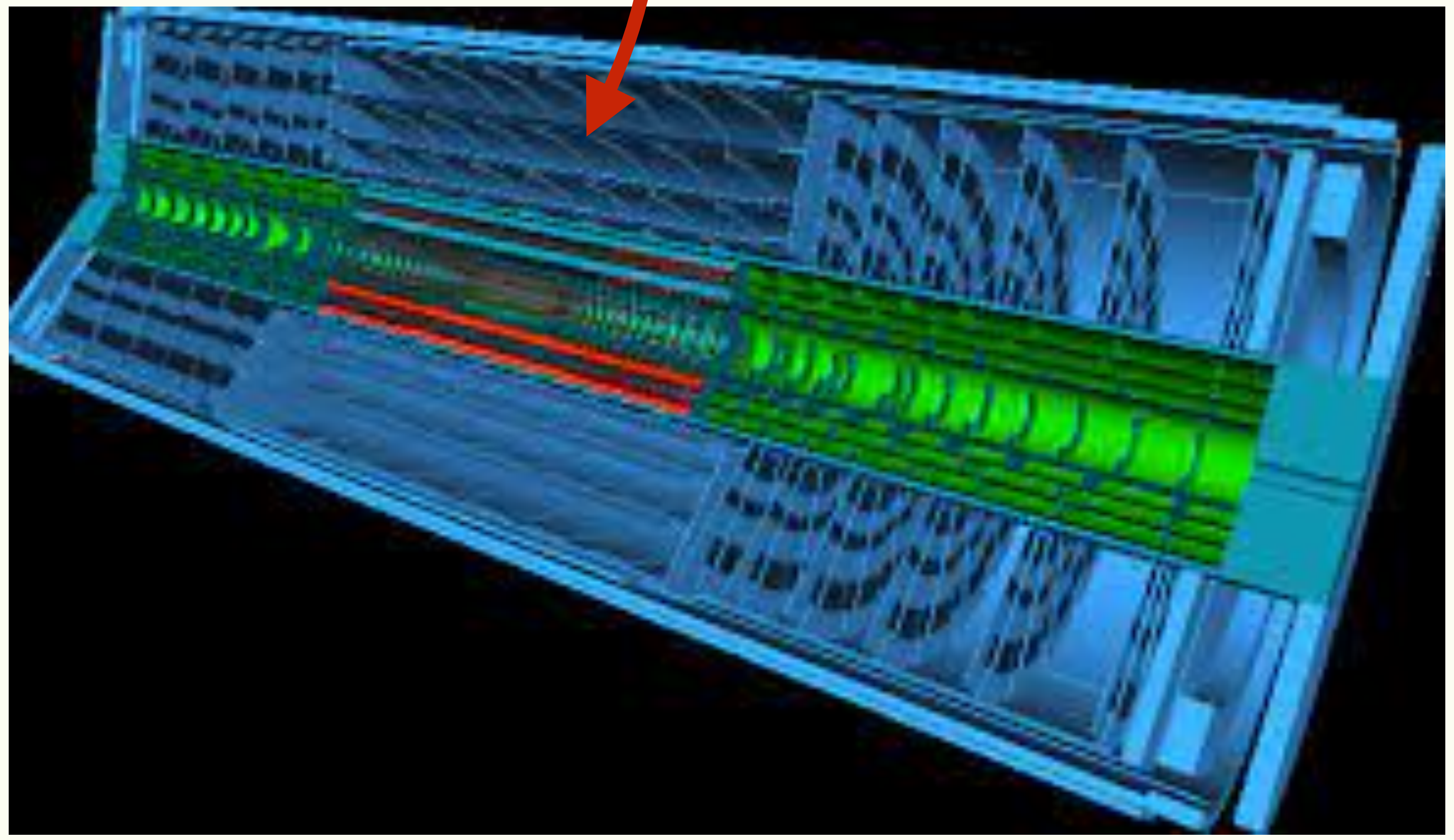
LHC → Upgrade → **HL-LHC**

LHC	HL-LHC
2008 - 2025	2028 ~
<μ> ~ 30	<μ> ~ 200
1×10^{34} cm^{-2}s^{-1}	7.5×10^{34} cm^{-2}s^{-1}
400 fb^{-1} (190 fb^{-1} so far)	4000 fb^{-1}

ATLAS "Current" Inner Detector



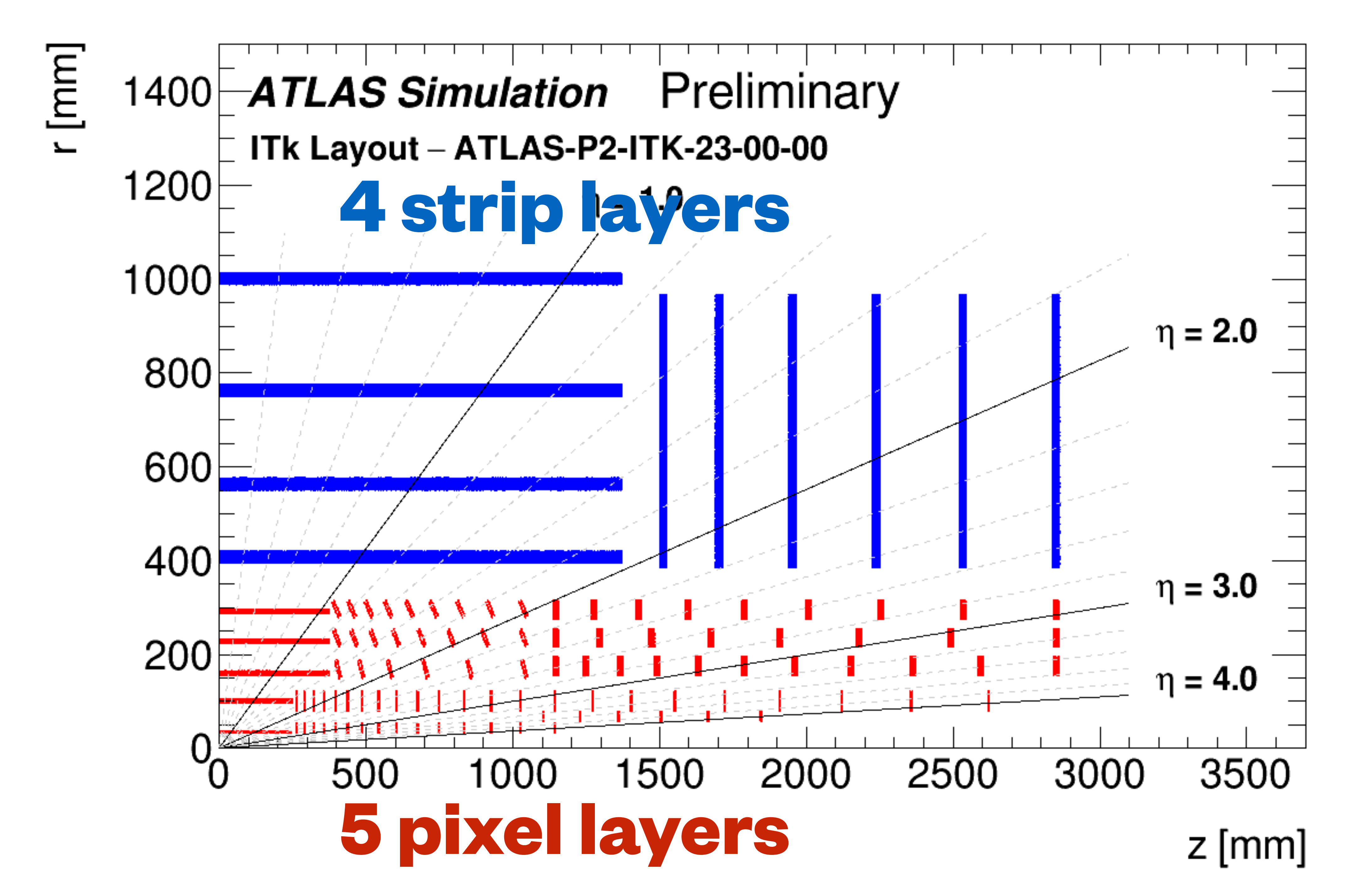




The current Inner Detector will be replaced by an all silicon Inner Tracker

ATLAS Inner Tracker Upgrade

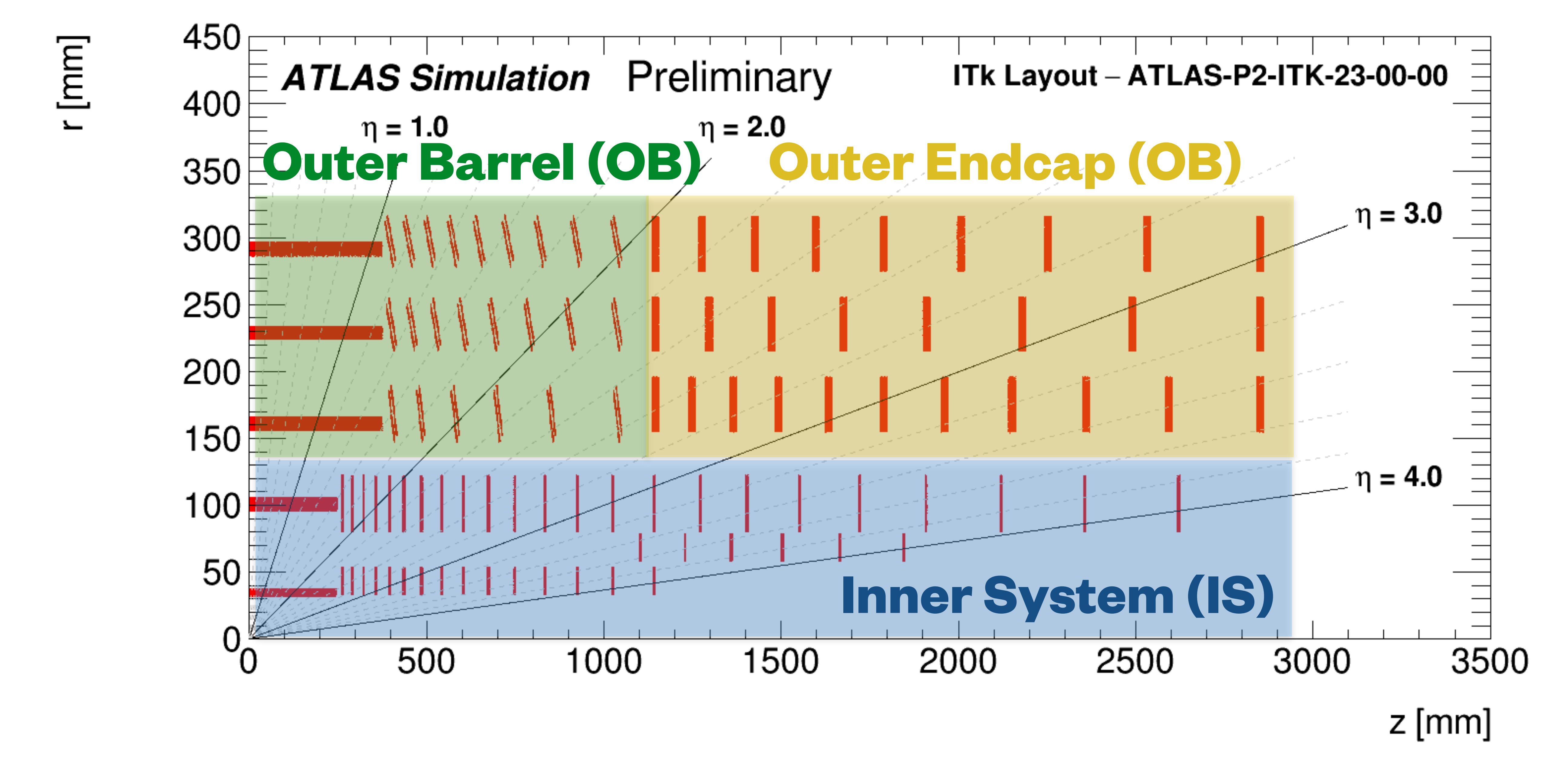
- **New Inner detector have to cope with the HL-LHC environment**
  - **Better radiation tolerance**
    - Fluence of 2 x 10^{16} n_{eq}/cm^2, 4000 fb^{-1}
  - **Faster readout**
    - 5 Gbit/s per data link
  - **Finer granularity**
    - keep ~ 1% occupancy



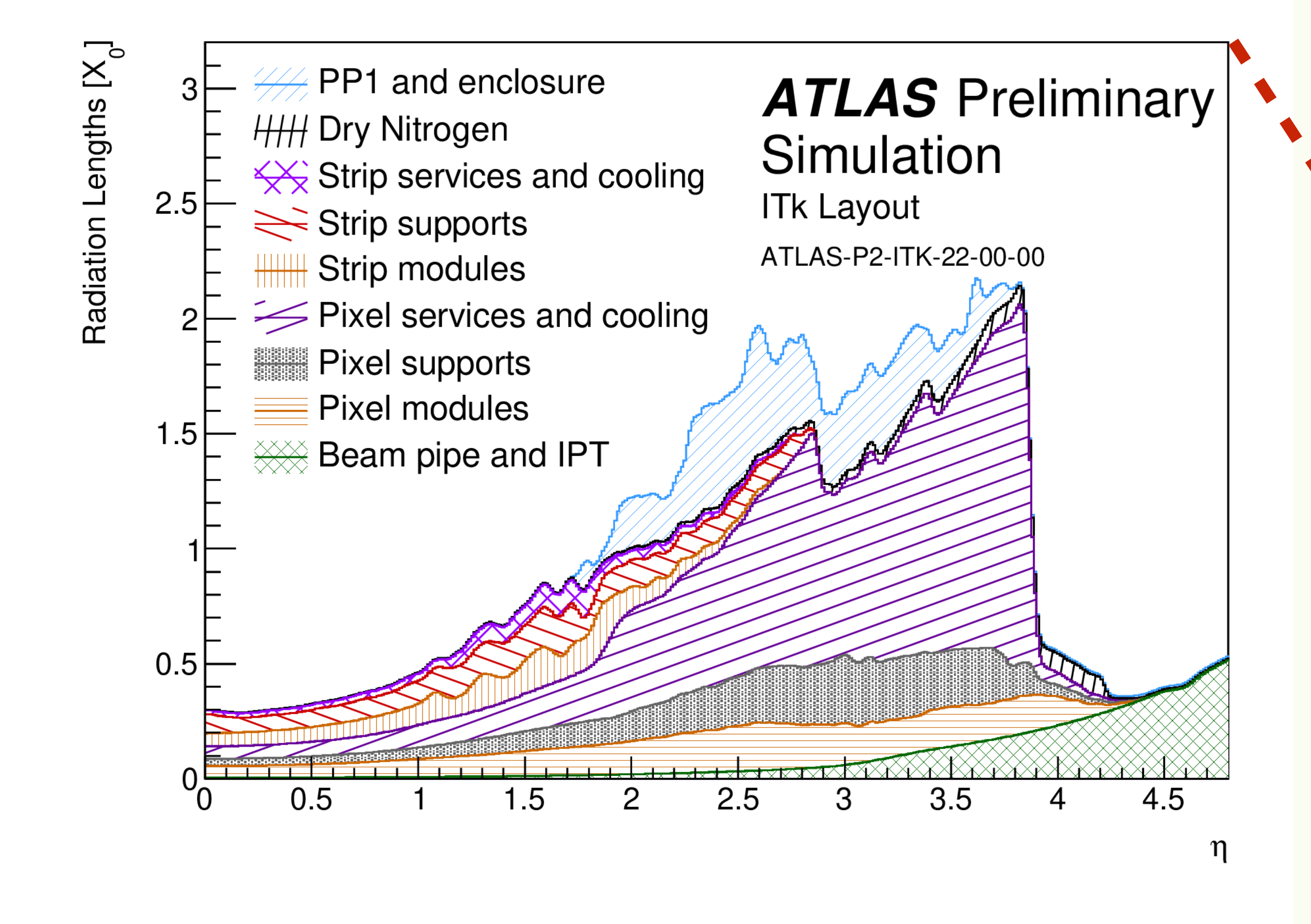
	Current ID	ITk
Covered area (Pix) [m^2]	1.9	13
Covered area (Strip) [m^2]	60	160
Readout channels (Pix)	~9.2 x 10^6	5 x 10^9
Readout channels (Strip)	~ 6 x 10^6	~ 50 x 10^6
$\|\eta\|$ coverage	2.5	4.0
Pixel size [μm^2]	50 x 400, 50 x 250	50 x 50, 25 x 100
L1 Trigger [kHz]	100	1000

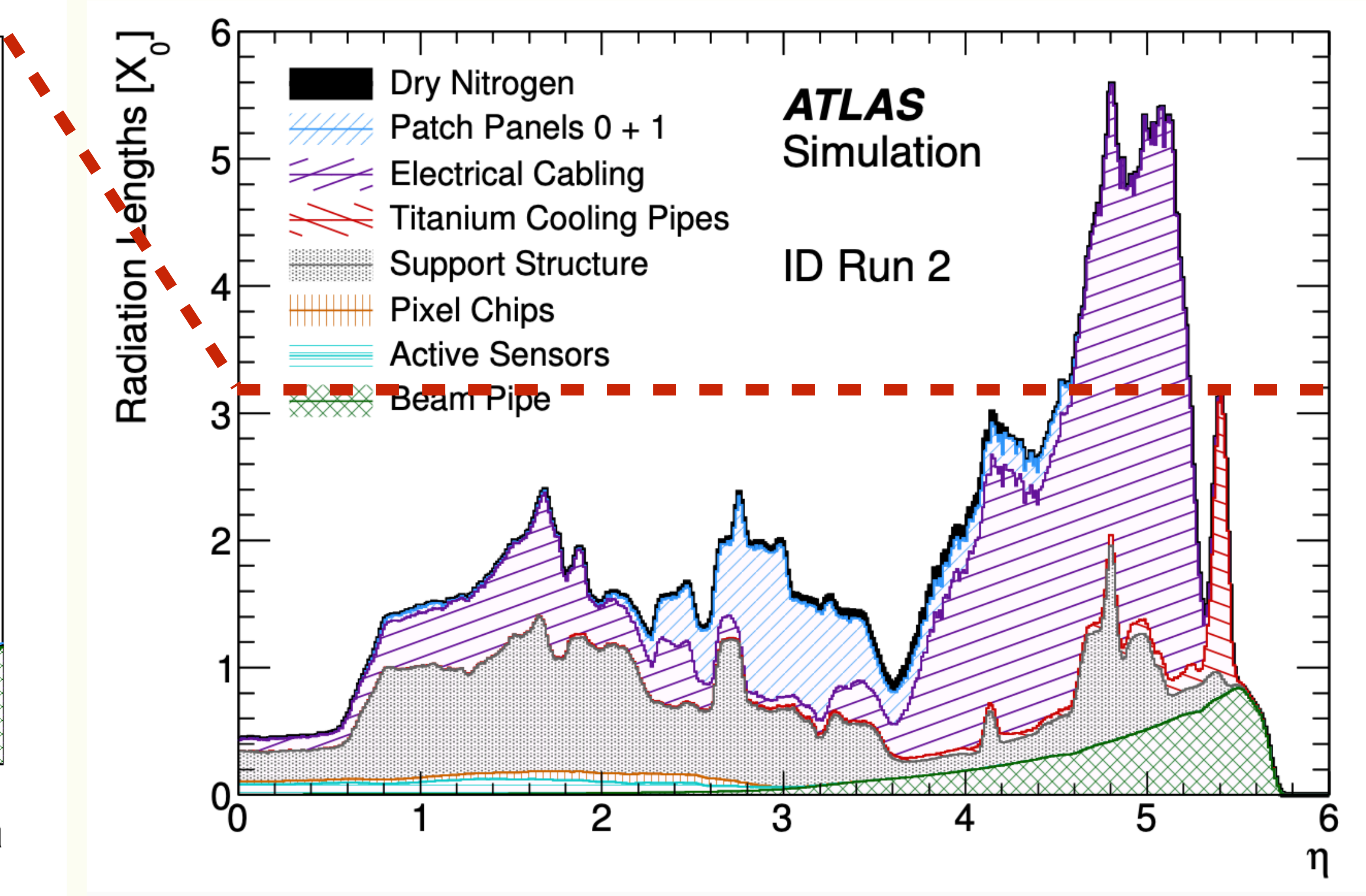
ITk Pixel Detector

- Key Concepts
  - Inner 2 layers are replaceable
  - Inclined modules
    - Minimise material and maximise acceptance
  - Larger covered area: 13 m^2, $|\eta| < 4$
    - Consists of ~ 10000 modules
  - Low material budget
  - 3D and planar sensors
  - Serial powering
  - Common front-end chip for all layers

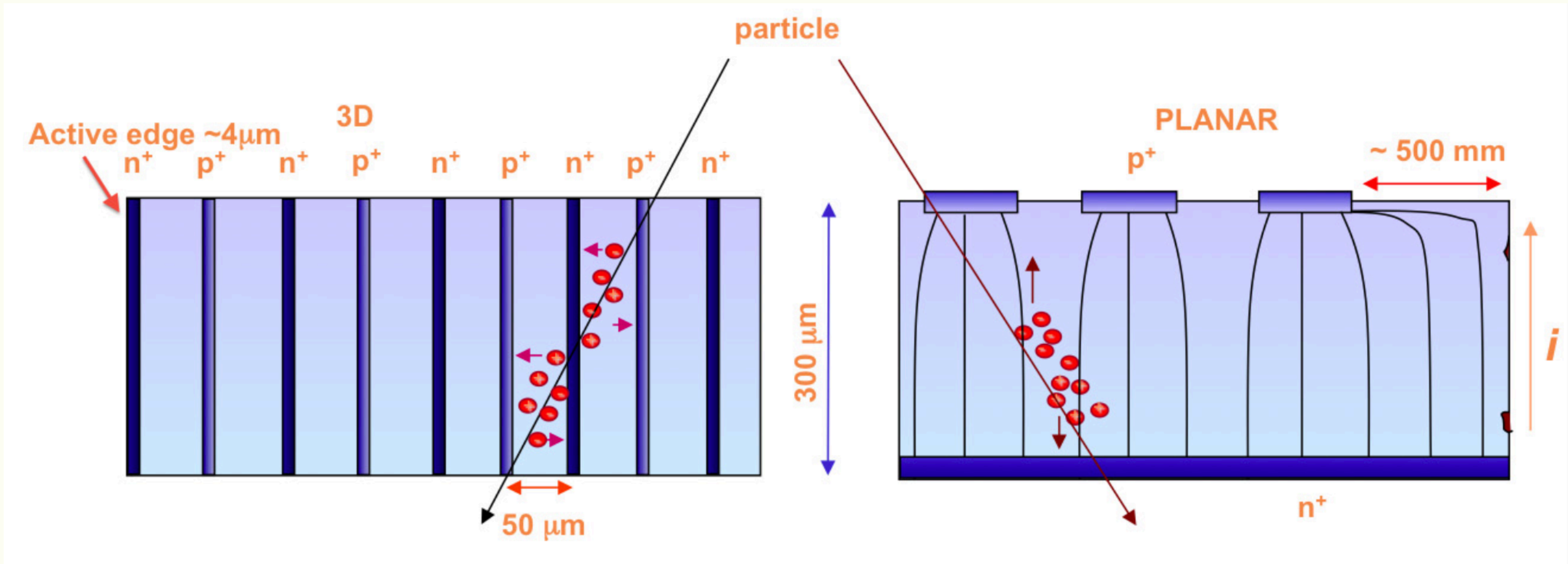


Radiation length





ITk Pixel Sensor



- Main change in sensor technology is the increase in the required level of tolerance to radiation
- 3D sensors: radiation hardness, low power dissipation
  - At the innermost layer (L0)
  - in the triplet modules
- Planner sensors: high fabrication yield and lower costs
  - In all other layers (L1-L4)
  - In the quad modules

Luminosity	Layer	Location	R (cm)	z (cm)	Fluence (10^{14} n_{eq}/cm^2)	Dose (MGy)
2000 fb^{-1}	0	flat barrel	3.9	0.0	131	-
			4.0	24.3	-	7.2
		inclined barrel	3.7	25.9	123	-
			3.7	110.0	-	9.9
		end-cap	5.1	123.8	68	6.3
2000 fb^{-1}	1	flat barrel	9.9	24.3	27	1.5
		inclined barrel	8.1	110.0	35	2.9
		end-cap	7.9	299.2	38	3.2
4000 fb^{-1}	2-4	flat barrel	16.0	44.6	28	1.6
		inclined barrel	15.6	110.0	30	2.0
		end-cap	15.3	299.2	38	3.5

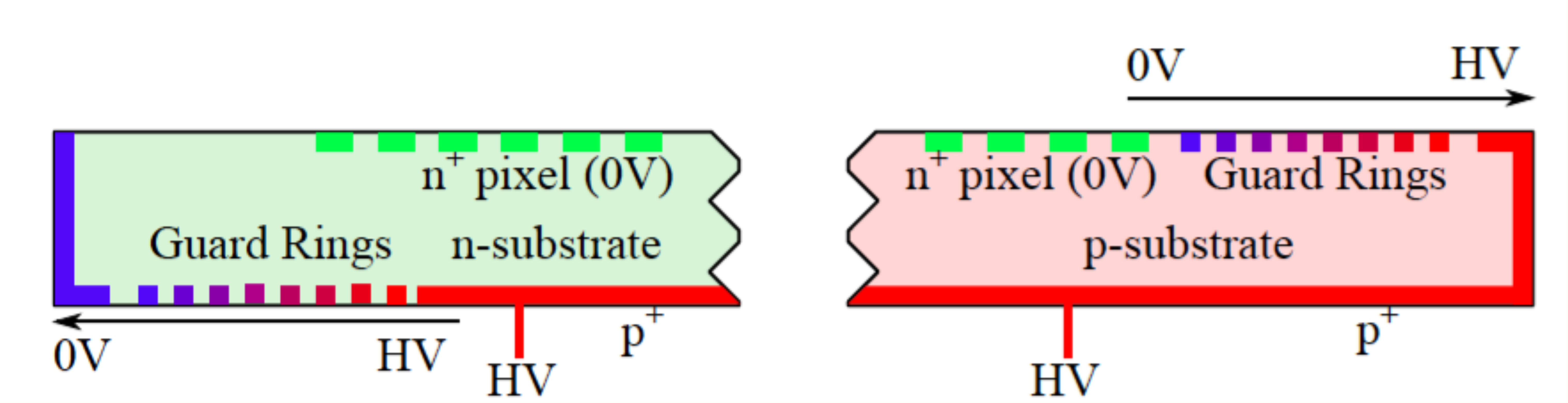
Planar Sensor

IBL

- Thickness of 200 μm
- 50 x 250 μm² pixel cells
- n-in-n

ITk

- Thickness of 100, 150 μm
- 50 x 50 μm² pixel cells
- n-in-p

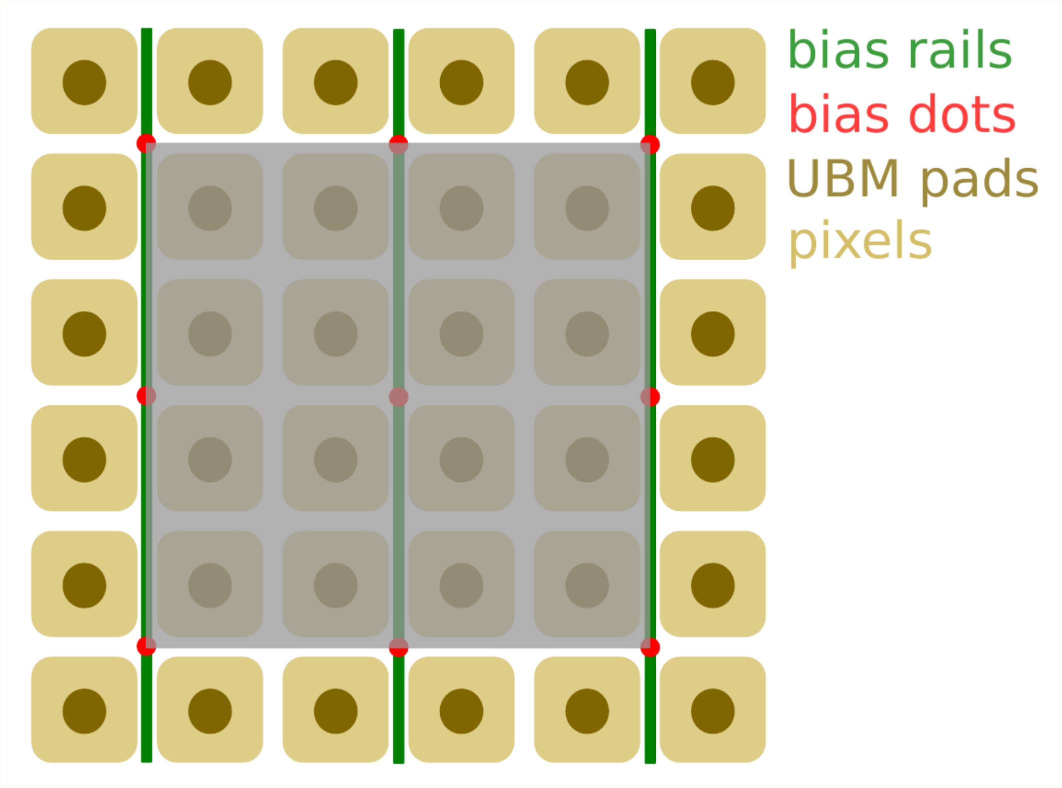


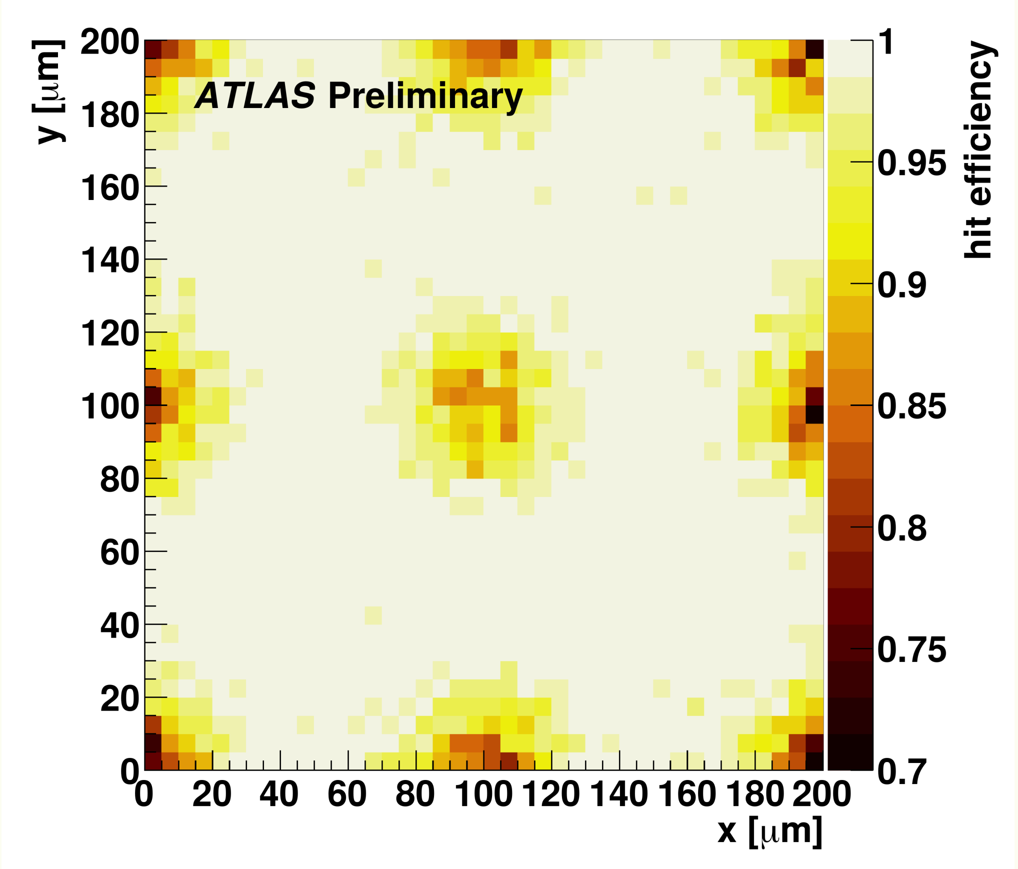
n-in-p technology

- Well proven and understood technique
- Single sided process (simple production, low cost)

Required Performance

- Hit efficiency > 97% (after irradiation)
- Bias voltage at end of life up to:
  - 600 V for 150 μm sensor
  - 400 V for 100 μm sensor



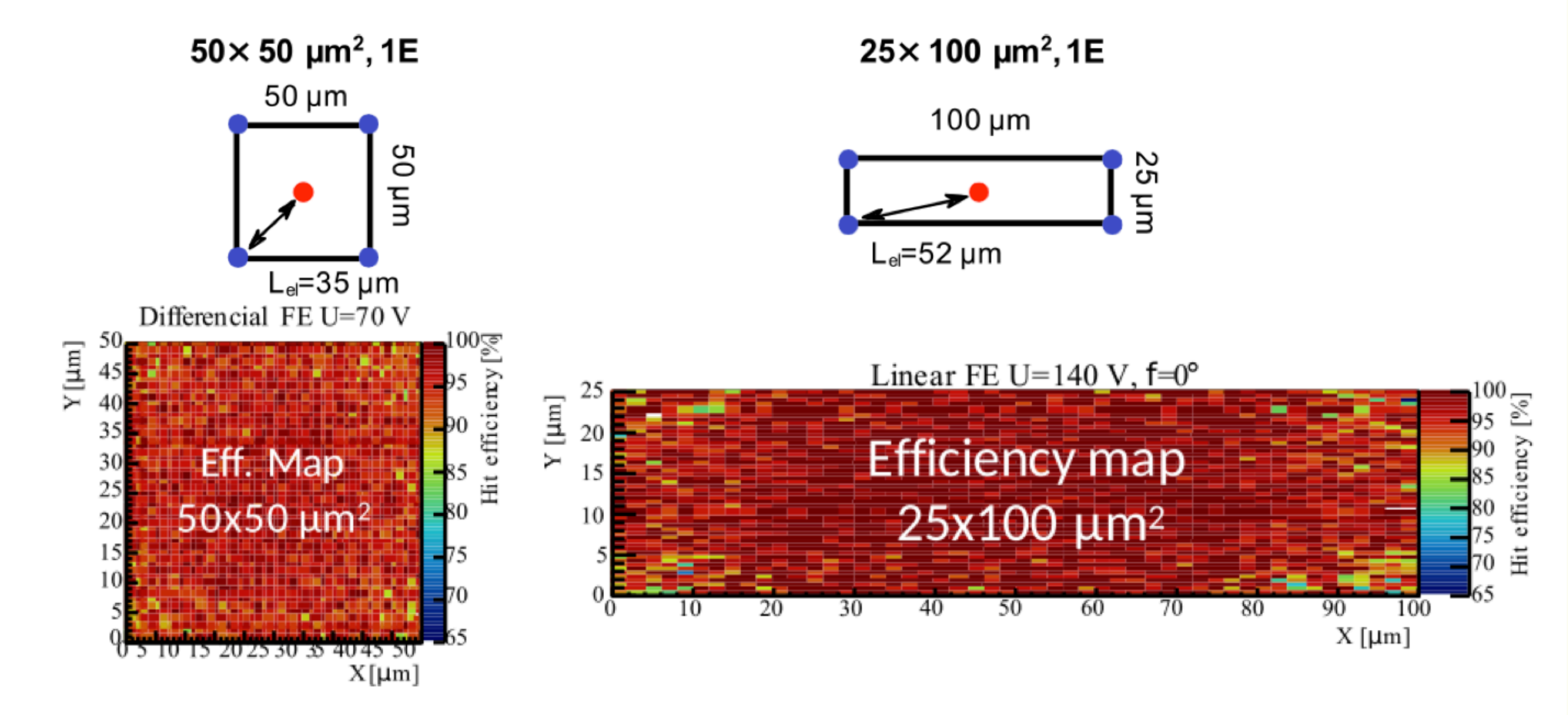


3D Sensor

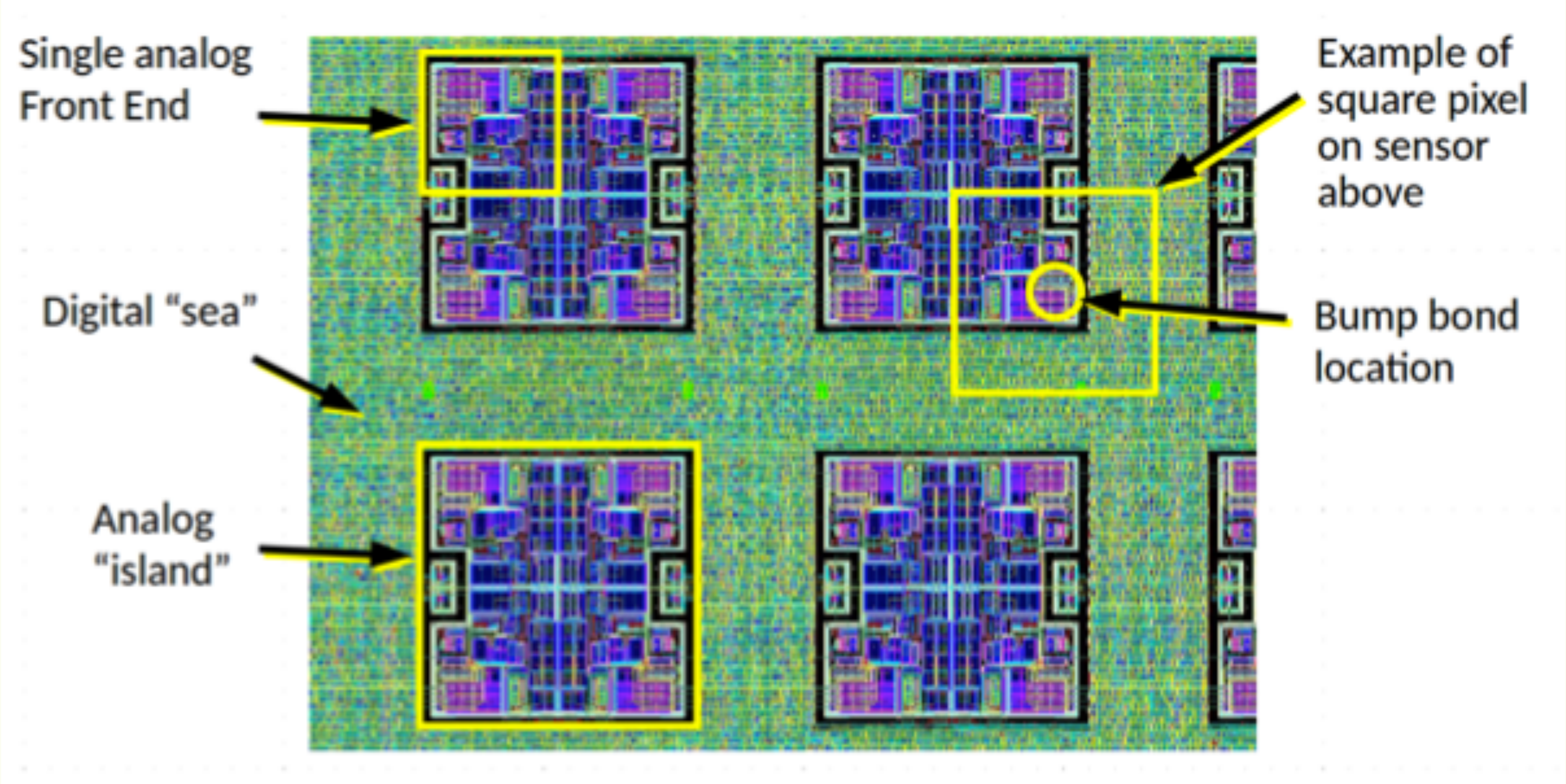
- 3D sensor used in the innermost layer
  - 150 μm active thickness + 100 μm support wafer
  - 50 x 50 μm² (endcap region)
  - 25 x 100 μm² (barrel region)
  - More radiation tolerant

Required Performance

- Hit efficiency > 97% (after irradiation)
- Low operational bias voltage: 80-140 V
- Low power dissipation



ITk Front-End Chip

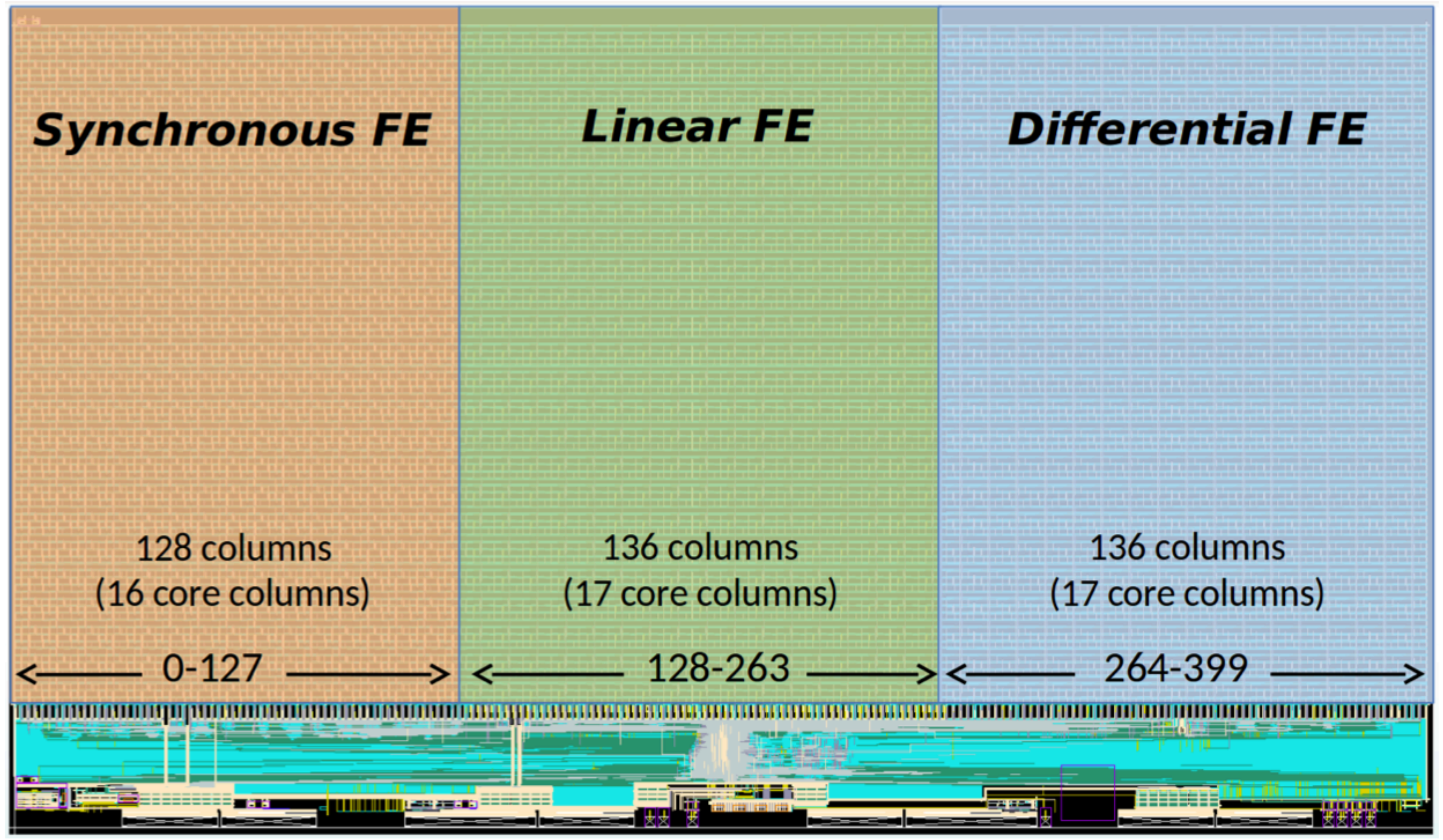


RD53 Collaboration

- ATLAS and CMS
- 65 nm TSMC technology (130 nm for IBL)
- 50 µm minimum pitch
- Shunt LDO implementation for compatibility with Serial Powering

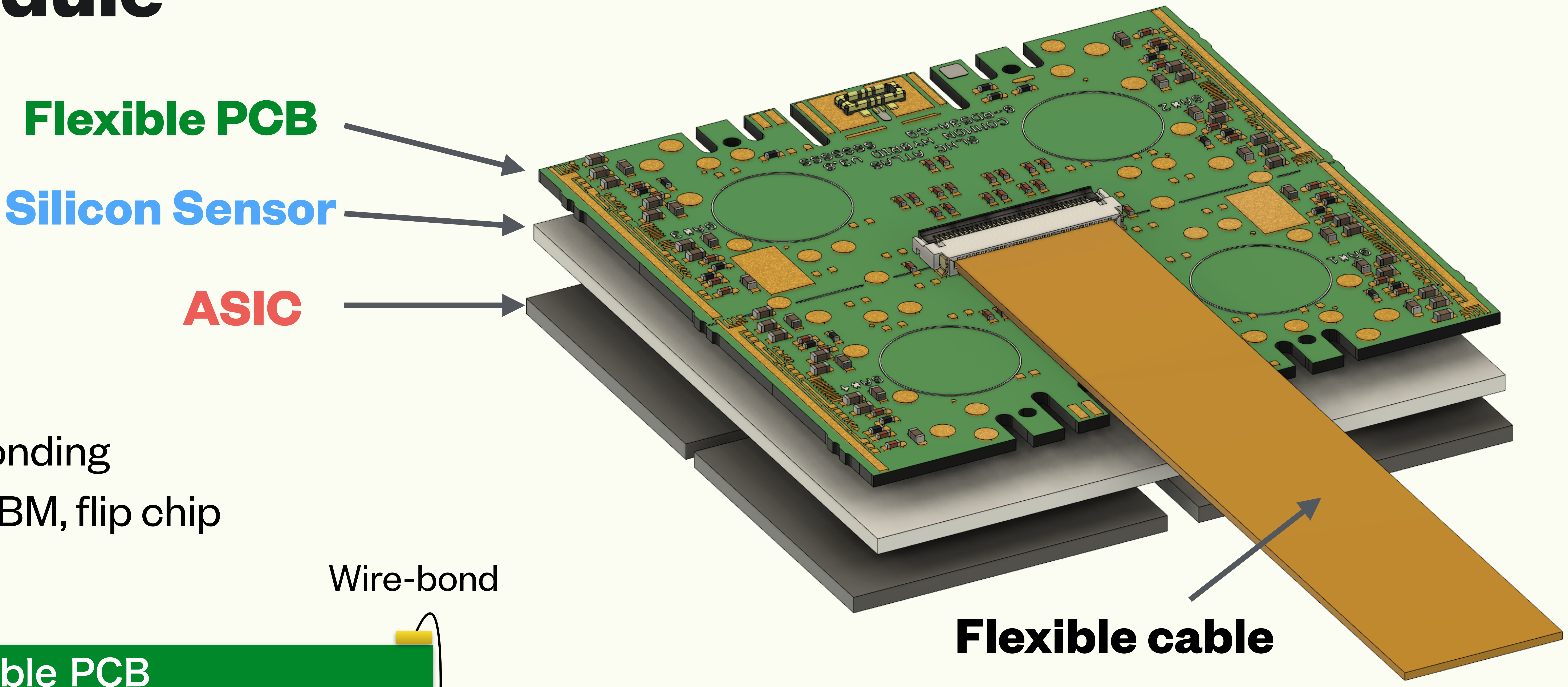
RD53A Prototype

- 3 different type FEs are on a single chip
- 400 x 192 pixels
- 50 x 50 μm^2



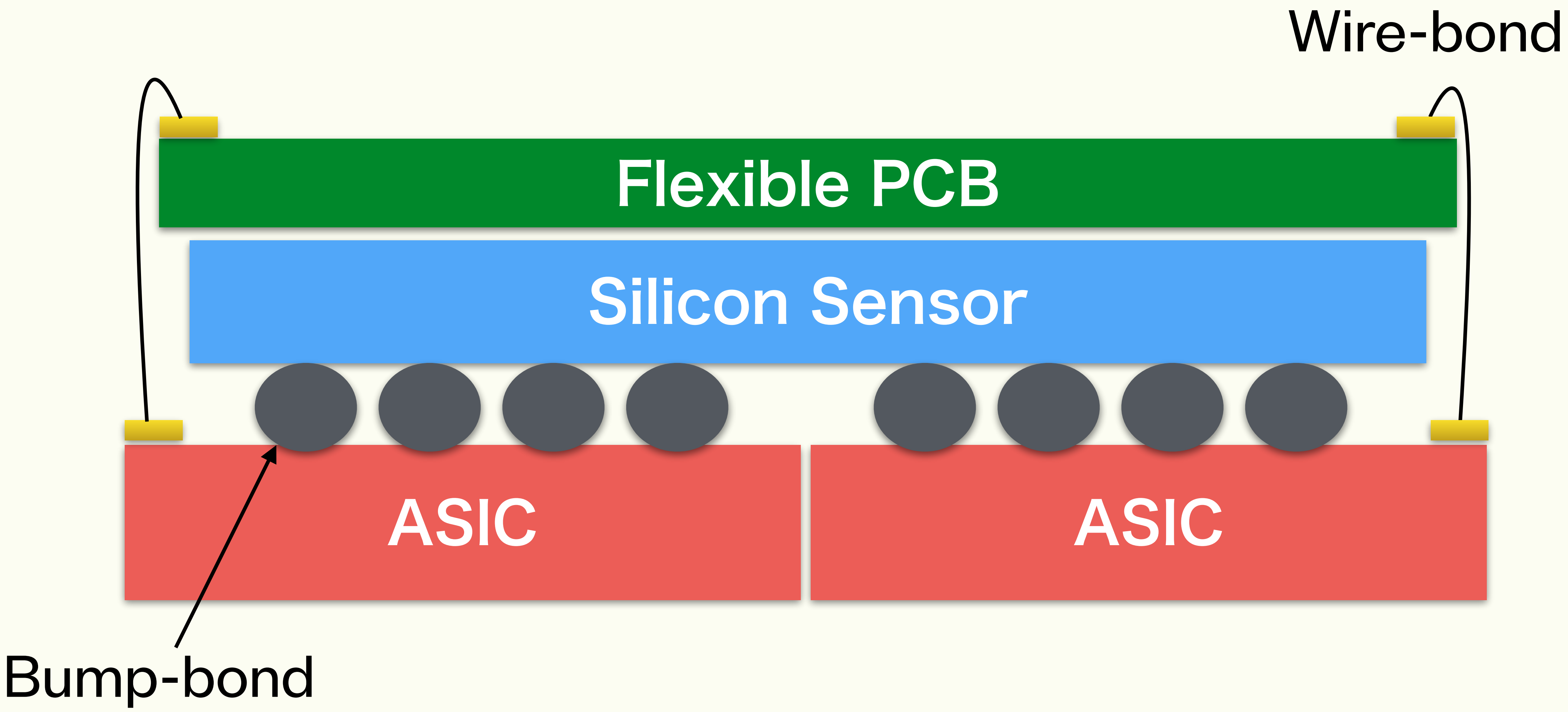
ITk Pixel Module

Quad module (40 x 40 mm²)



Hybridization

- Fine-pitch bump-bonding
- Bump deposition, UBM, flip chip



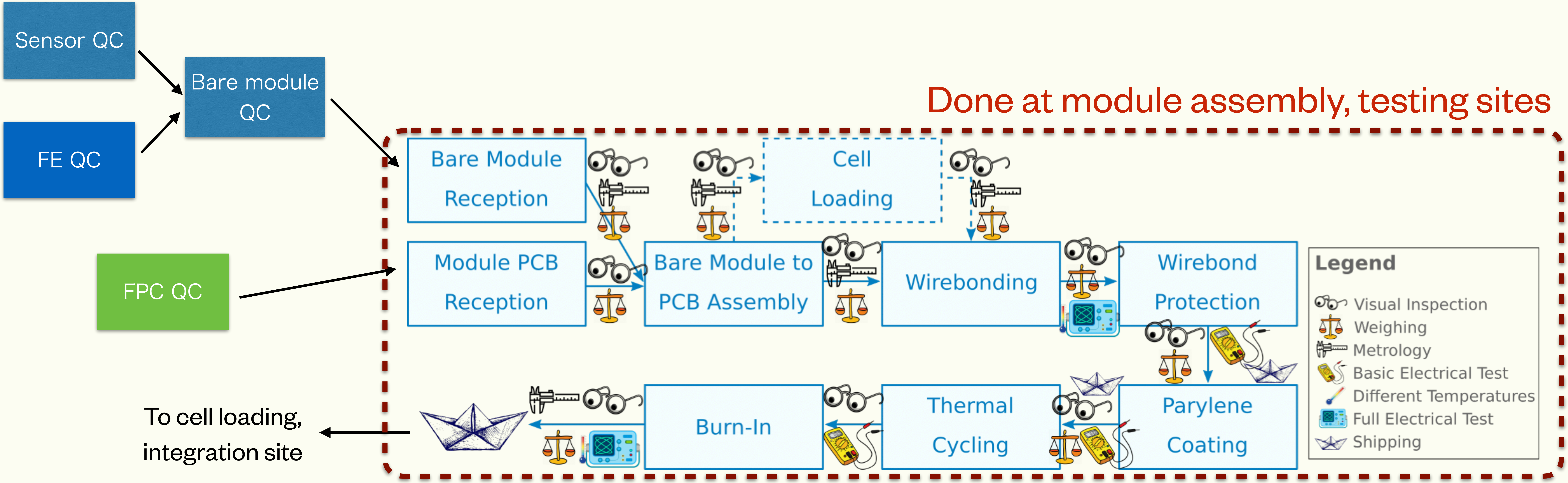
- 50 x 50 μm² pixel
- 1.28 Gb/s per lane

Module QC

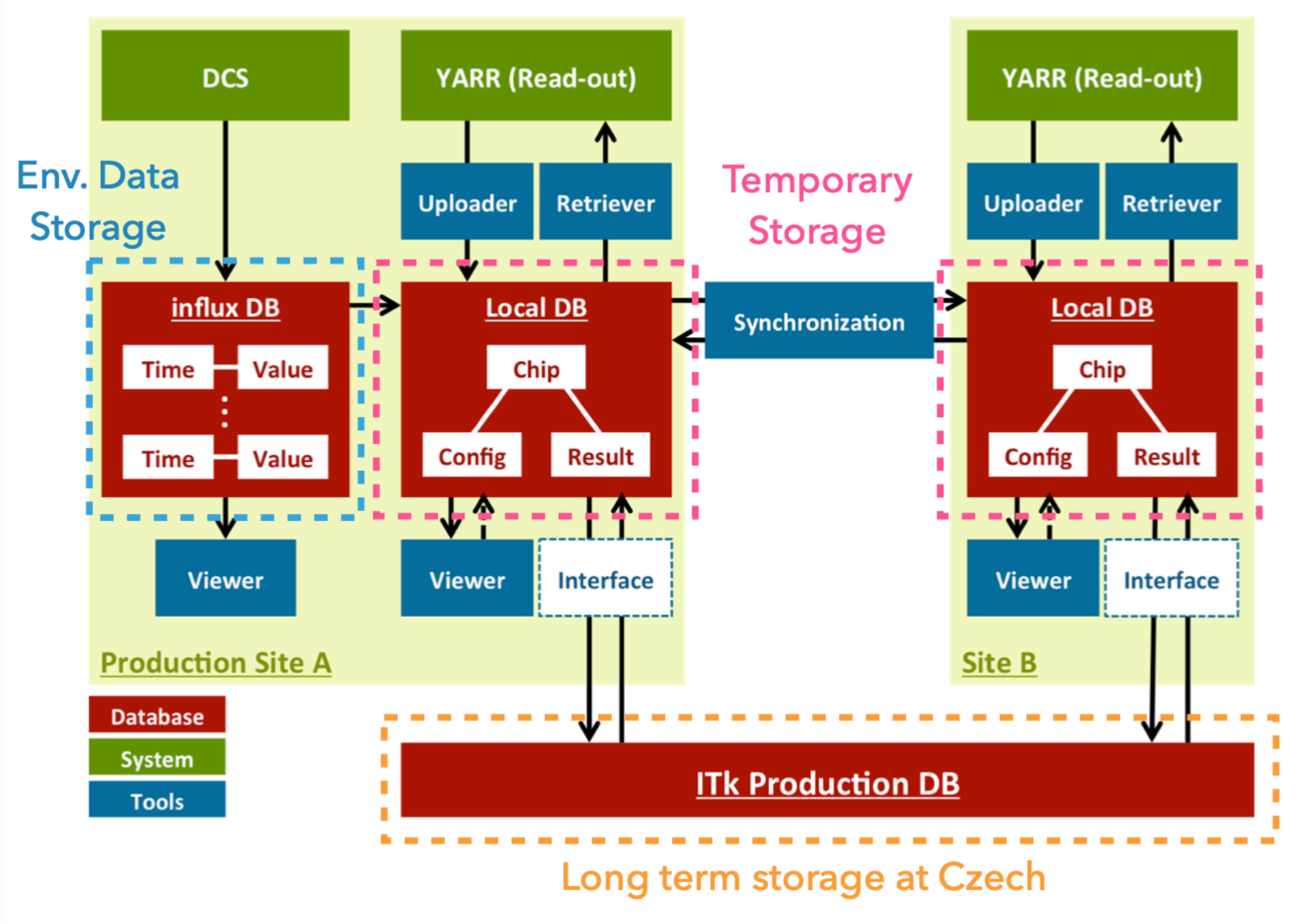
- All modules have to pass "module QC"
  - Many institutes (> 20) are joining in the Production

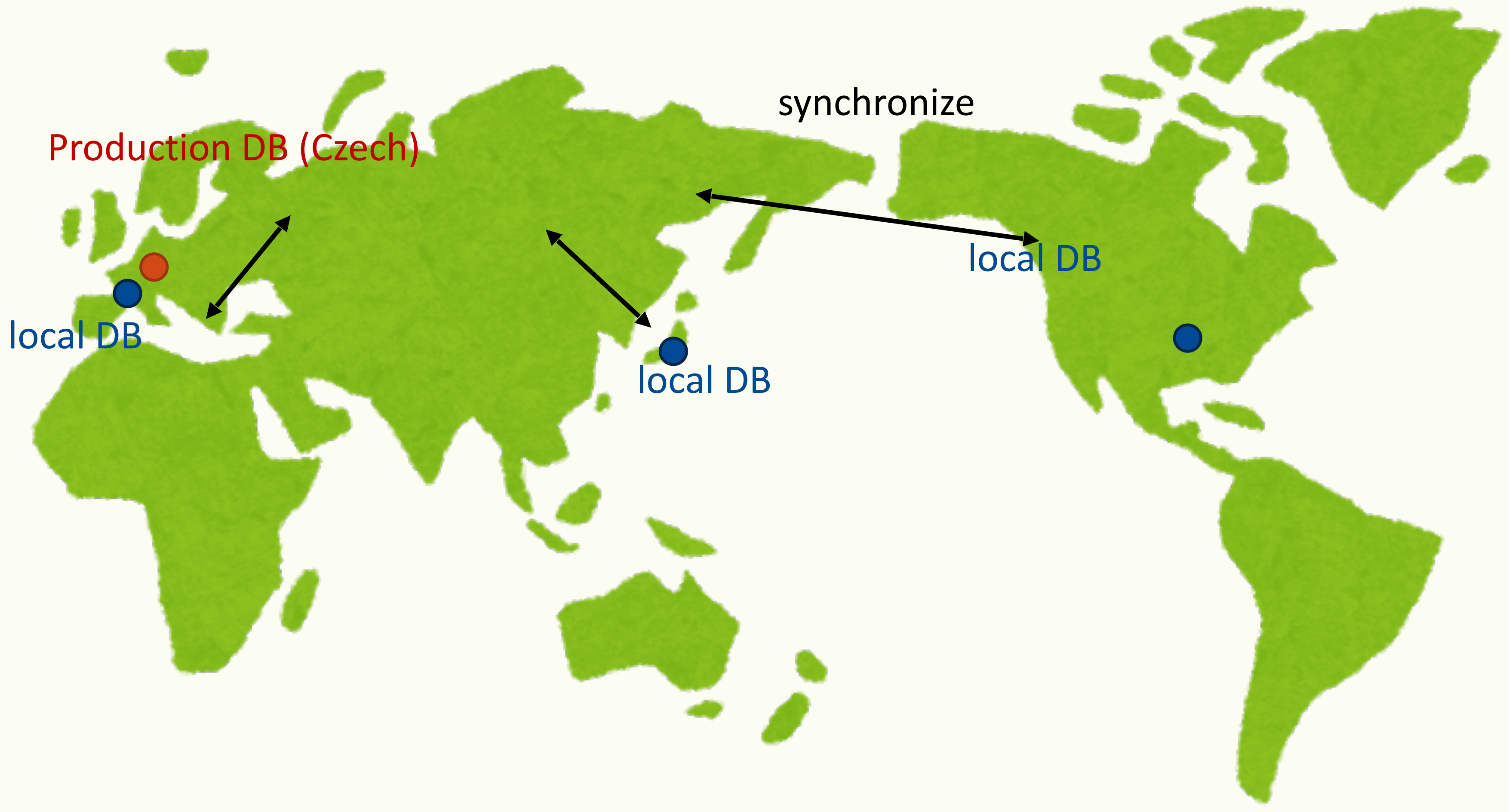
Difficulty for QC tests

- Perform comparable tests with variety of testing setup
- Properly handle testing data to compare between different stage/sites



Database





Central DB: ITk Production DB

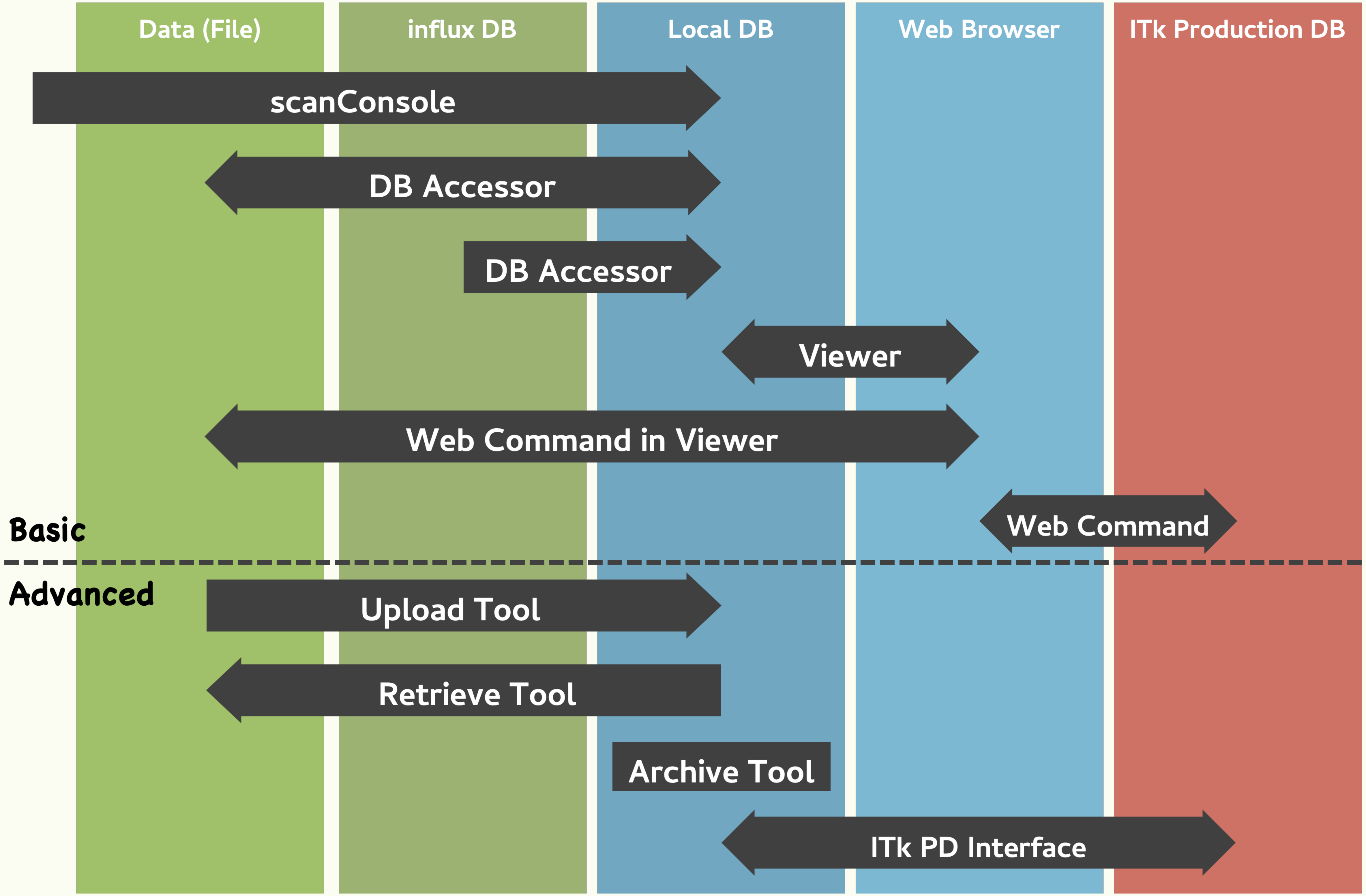
- Storage for all data of ITk

Local DB:

- Temporary storage of each site

Local DB influxdb

Data Flow


Data (File)
influx DB
Local DB
Web Browser
ITk Production DB
scanConsole
DB Accessor
DB Accessor
Viewer
Web Command in Viewer
Web Command
Basic
Advanced
Upload Tool
Retrieve Tool
Archive Tool
ITk PD Interface

Local Data Base

NoSQL Database

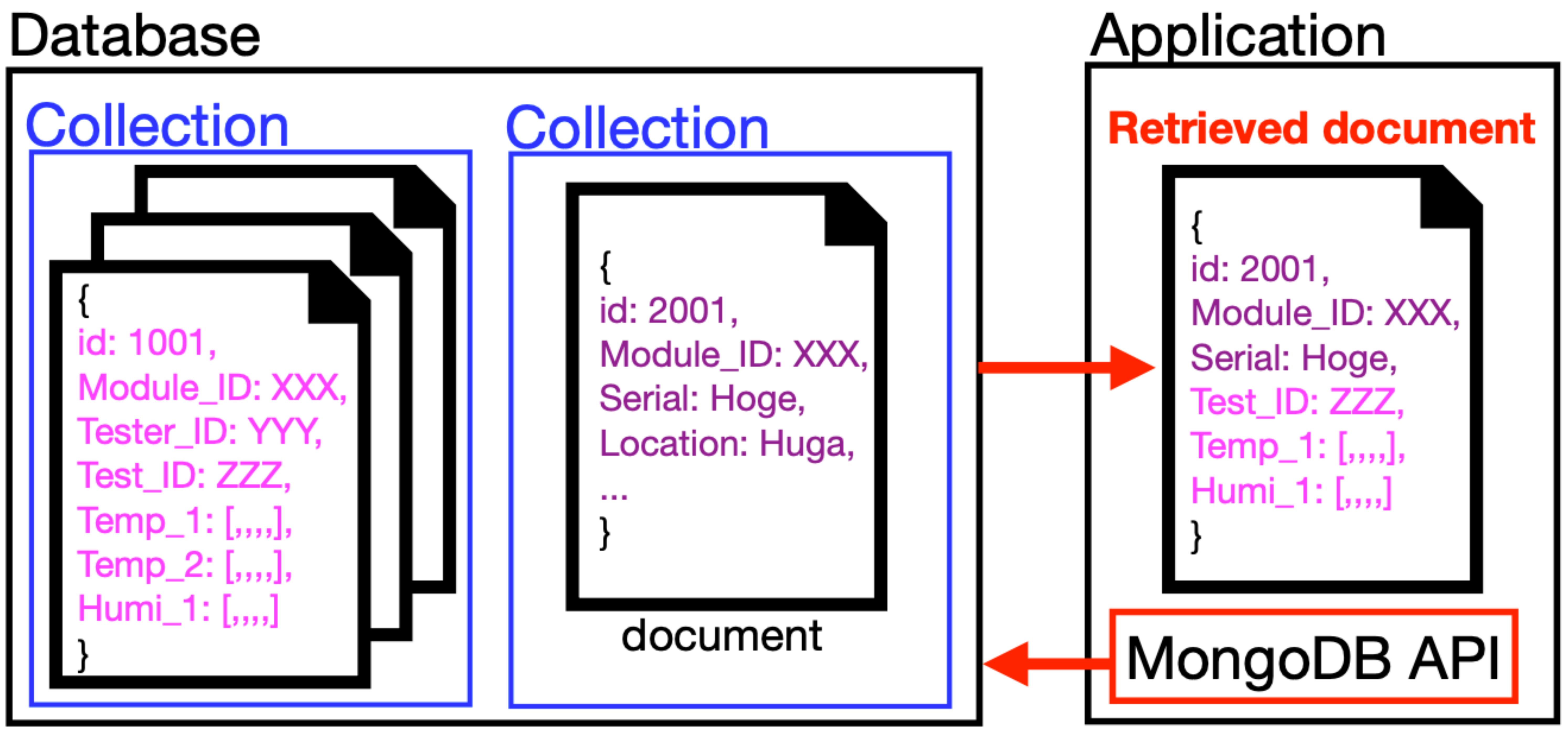
- Favoured due to its flexibility compared to SQL DB
- Data is stored as a “json” format (“document”)

SQL

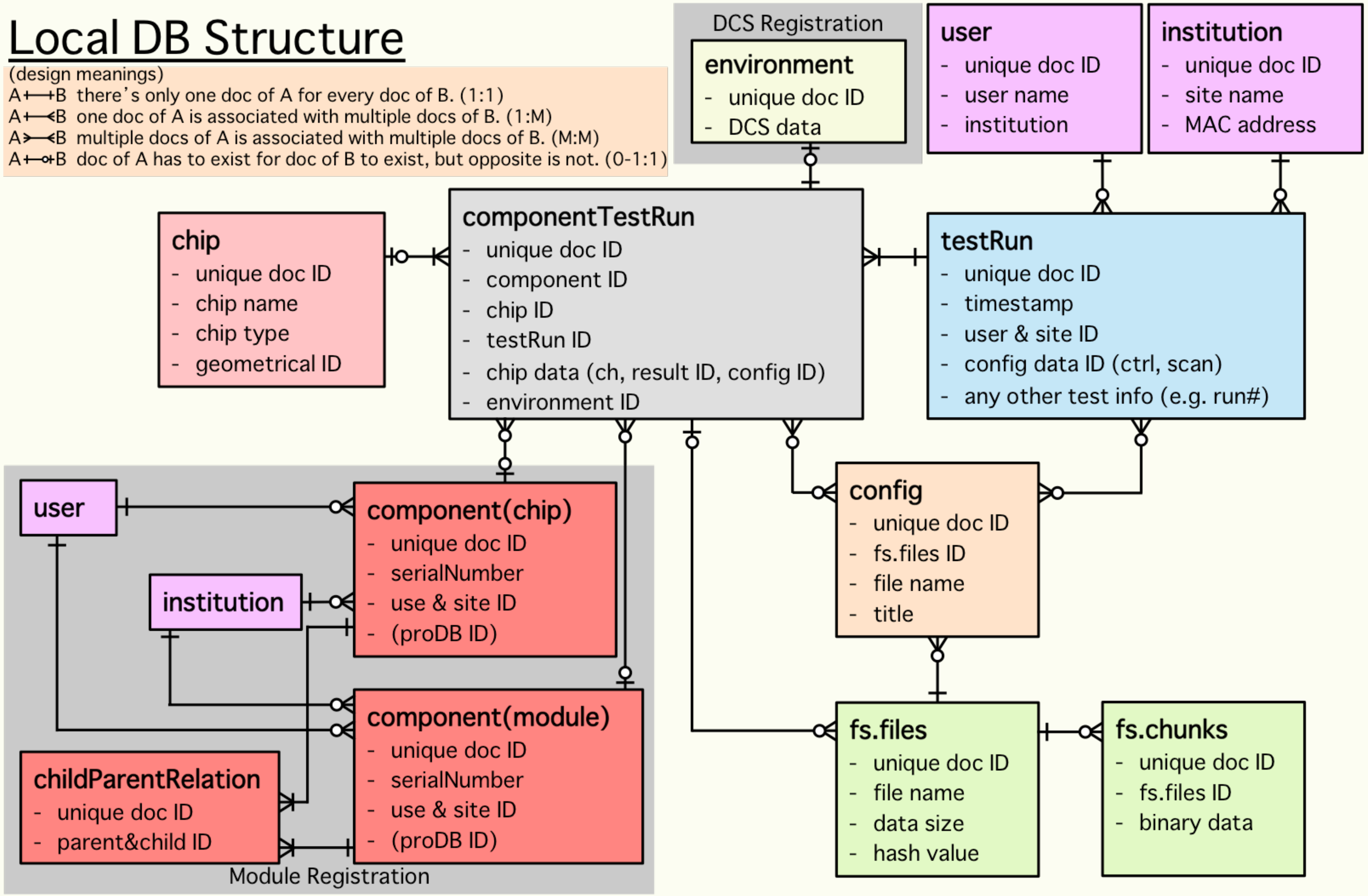
- Relational
- Structured data
- Vertically scalable
- Table based

NoSQL

- Non-relational
- Unstructured data
- Horizontally scalable
- Document, key-value, graph, or wide-column

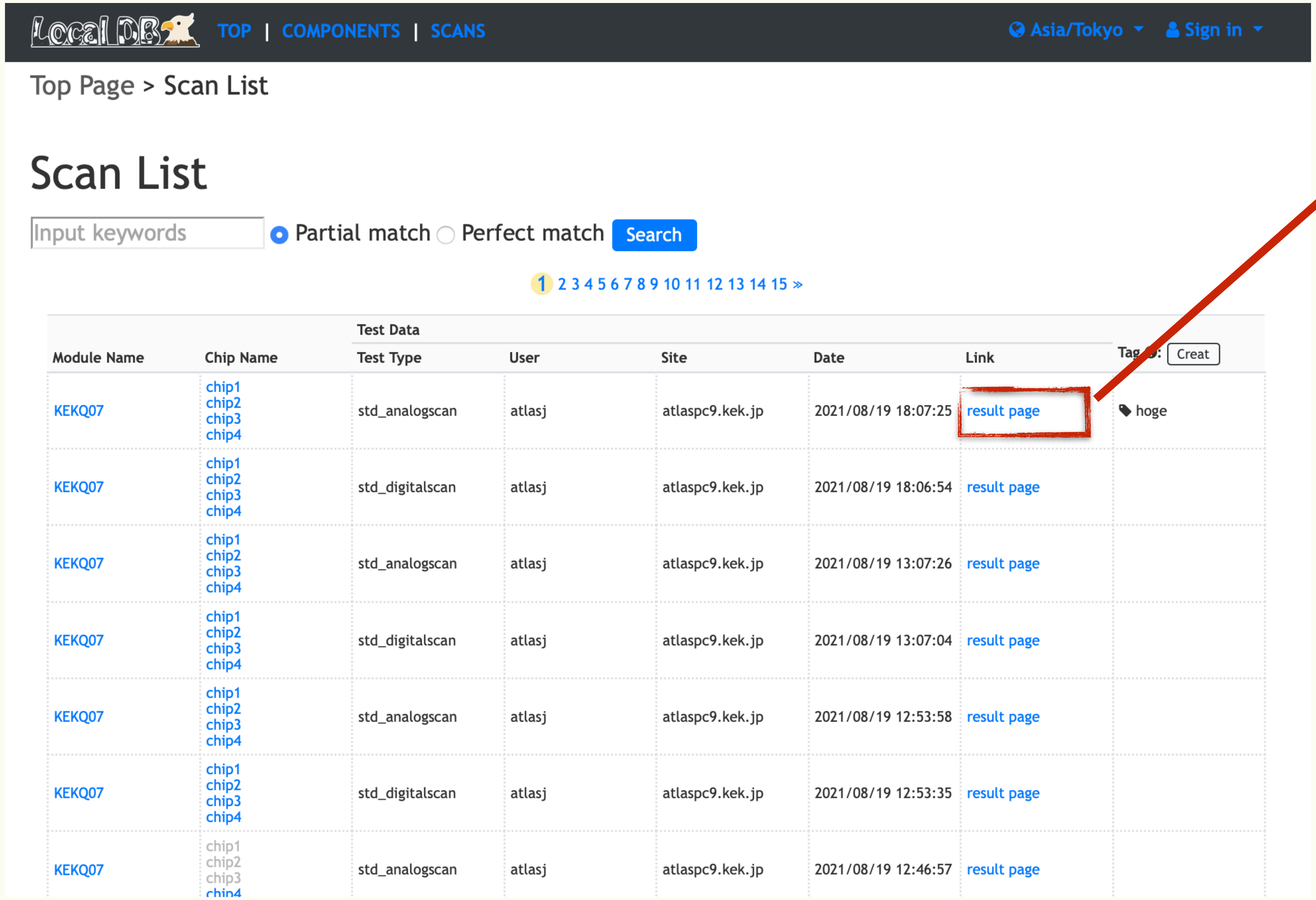


Structure of LocalDB



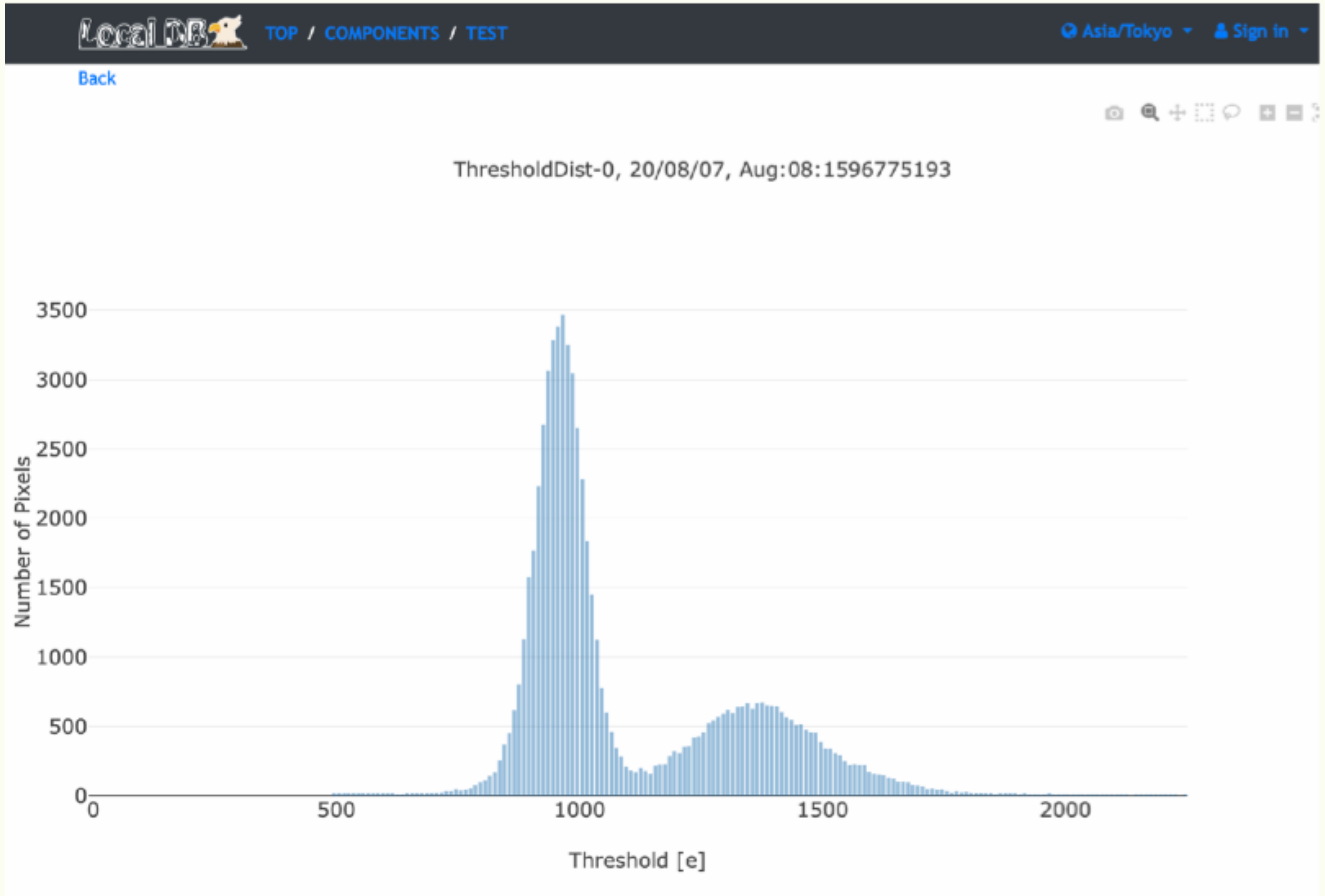
Local DB Viewer

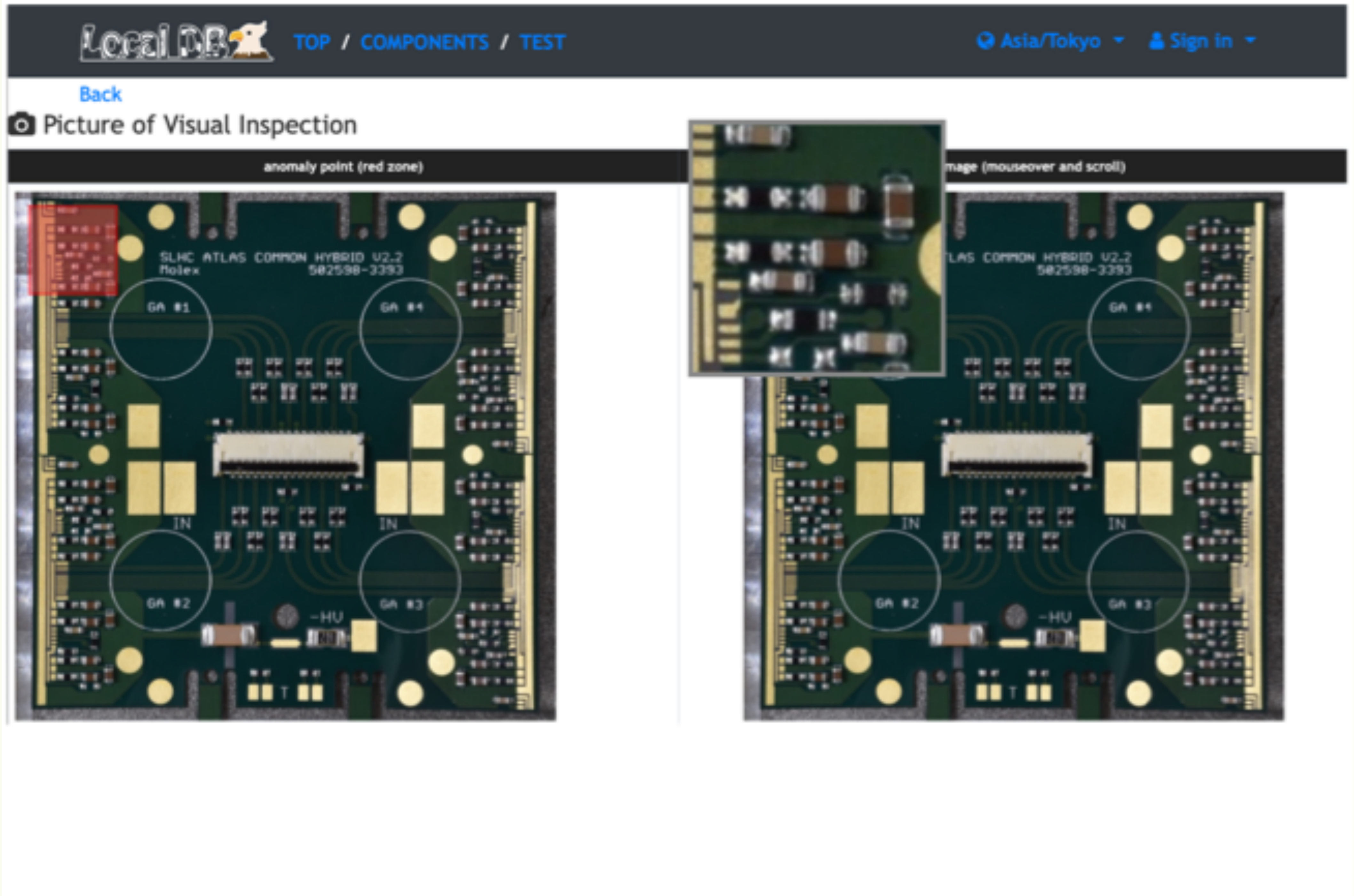
Custom Web application based on Flask



Local DB Viewer

Dynamically generate plots by ploty





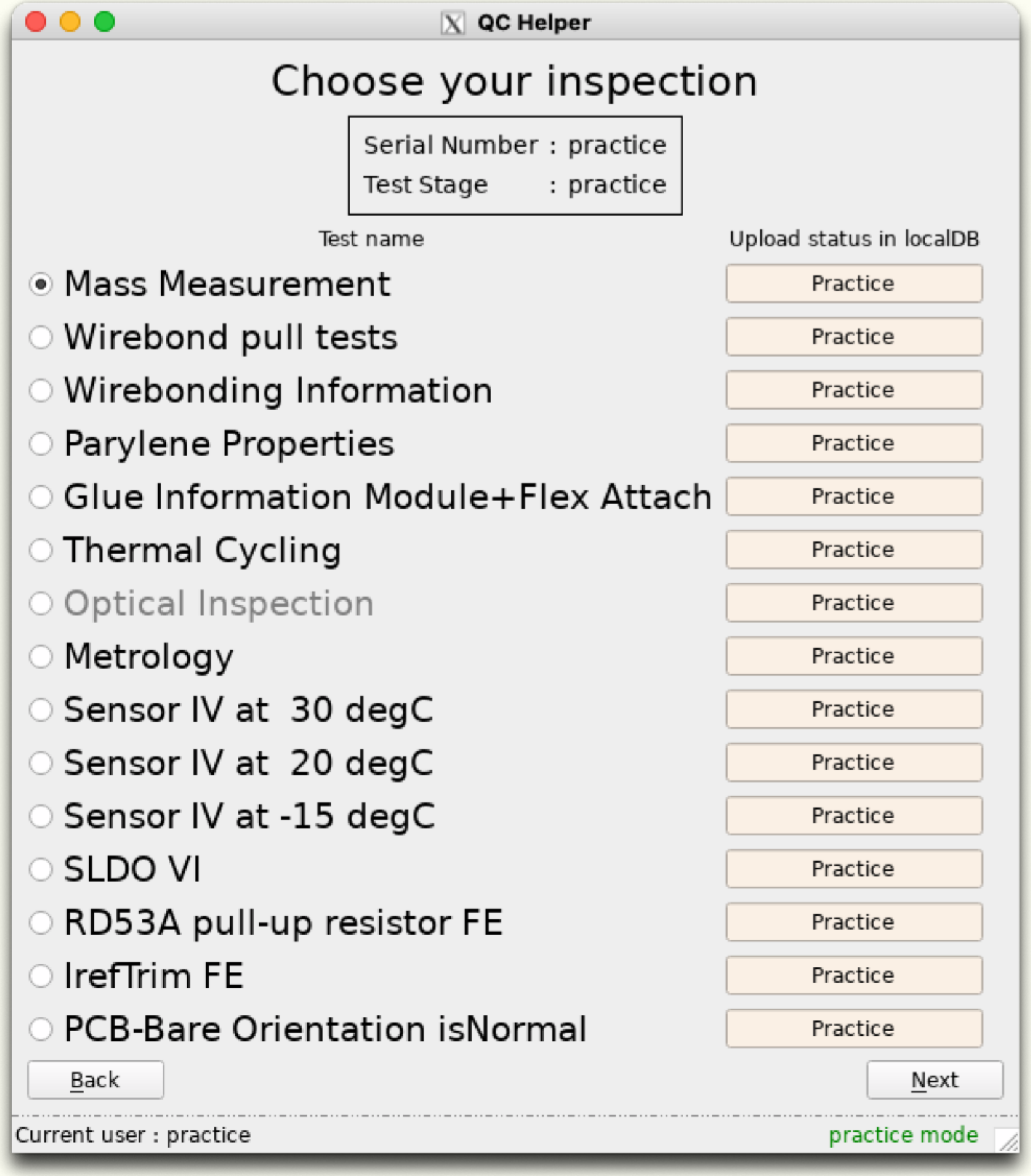
Environmental Data

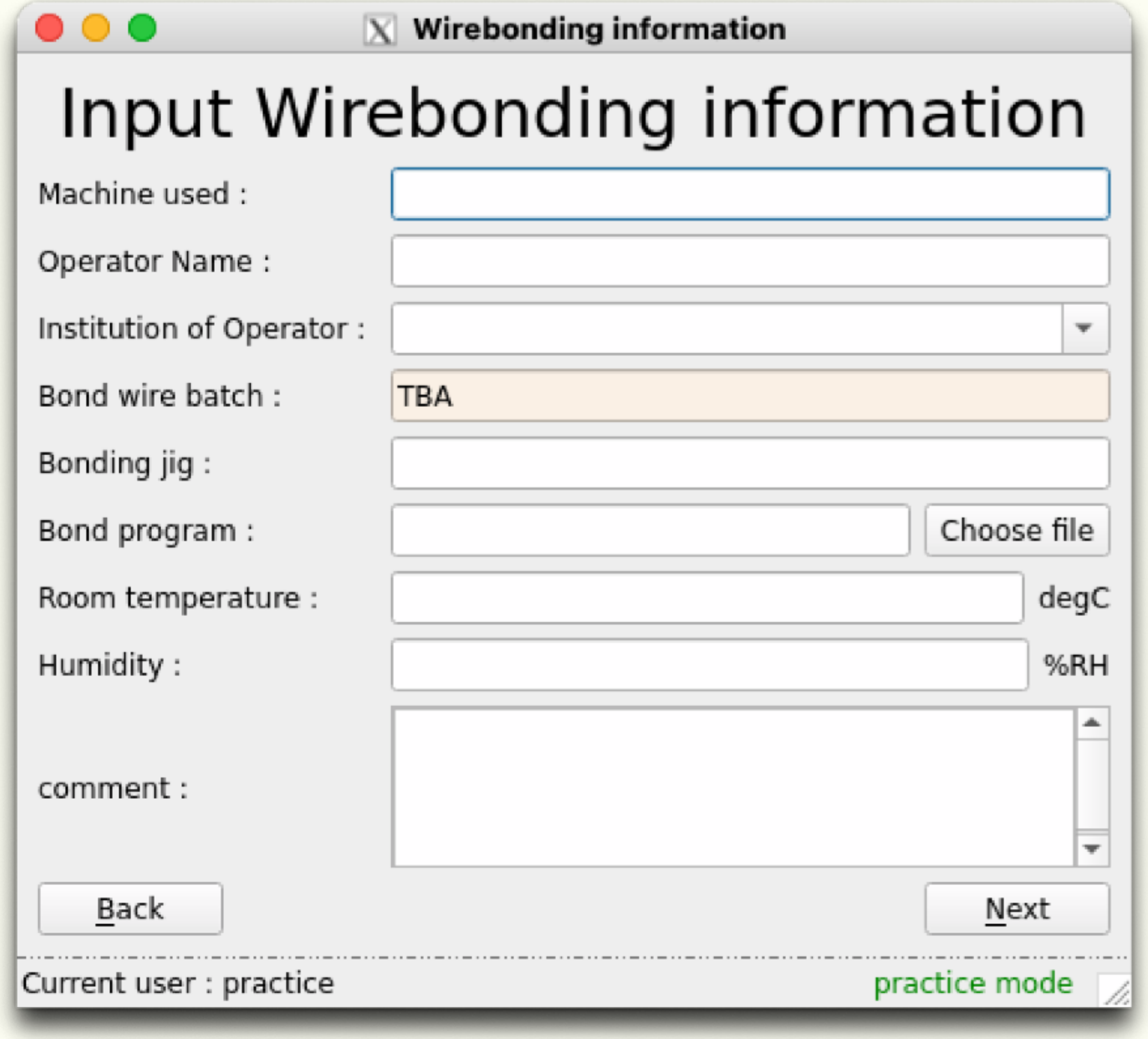
influxdb : Time series database for environmental monitoring

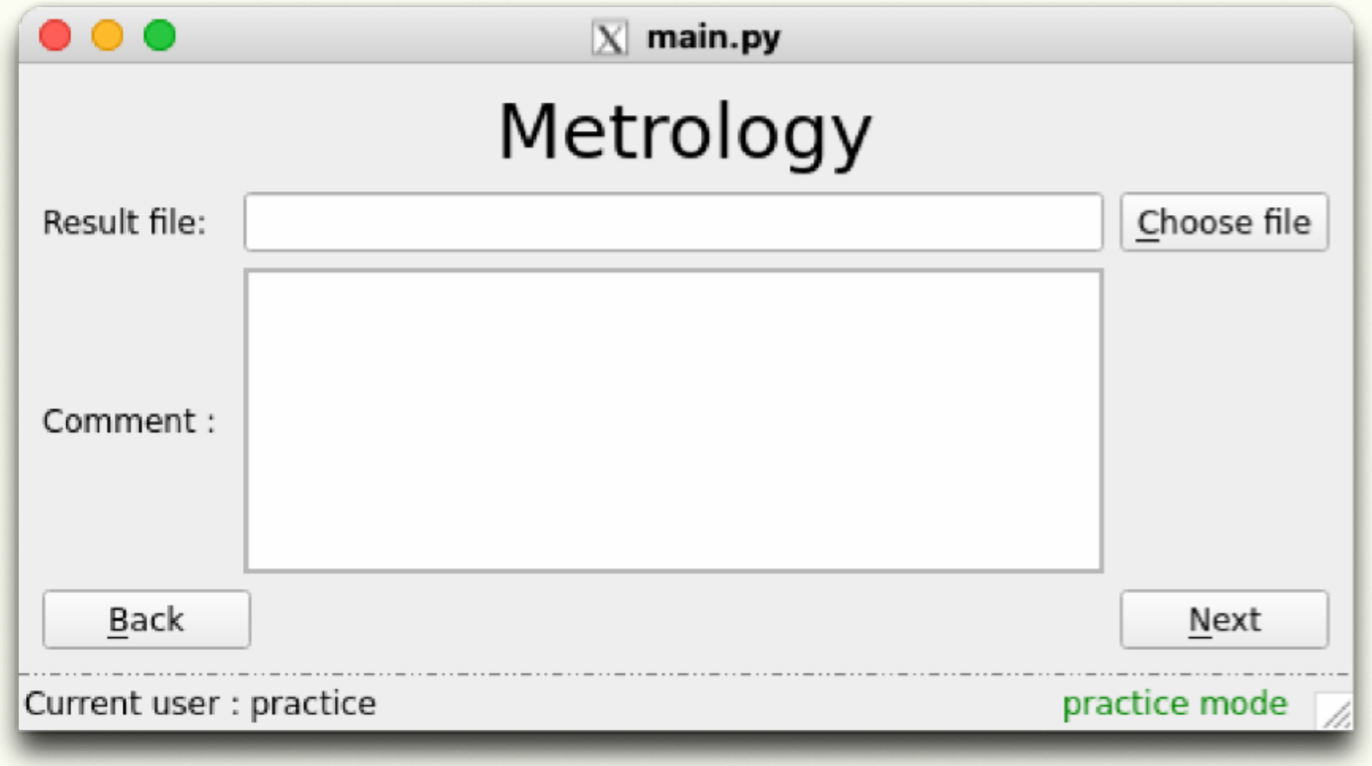
Grafana: Open source analytics and interactive visualisation web application

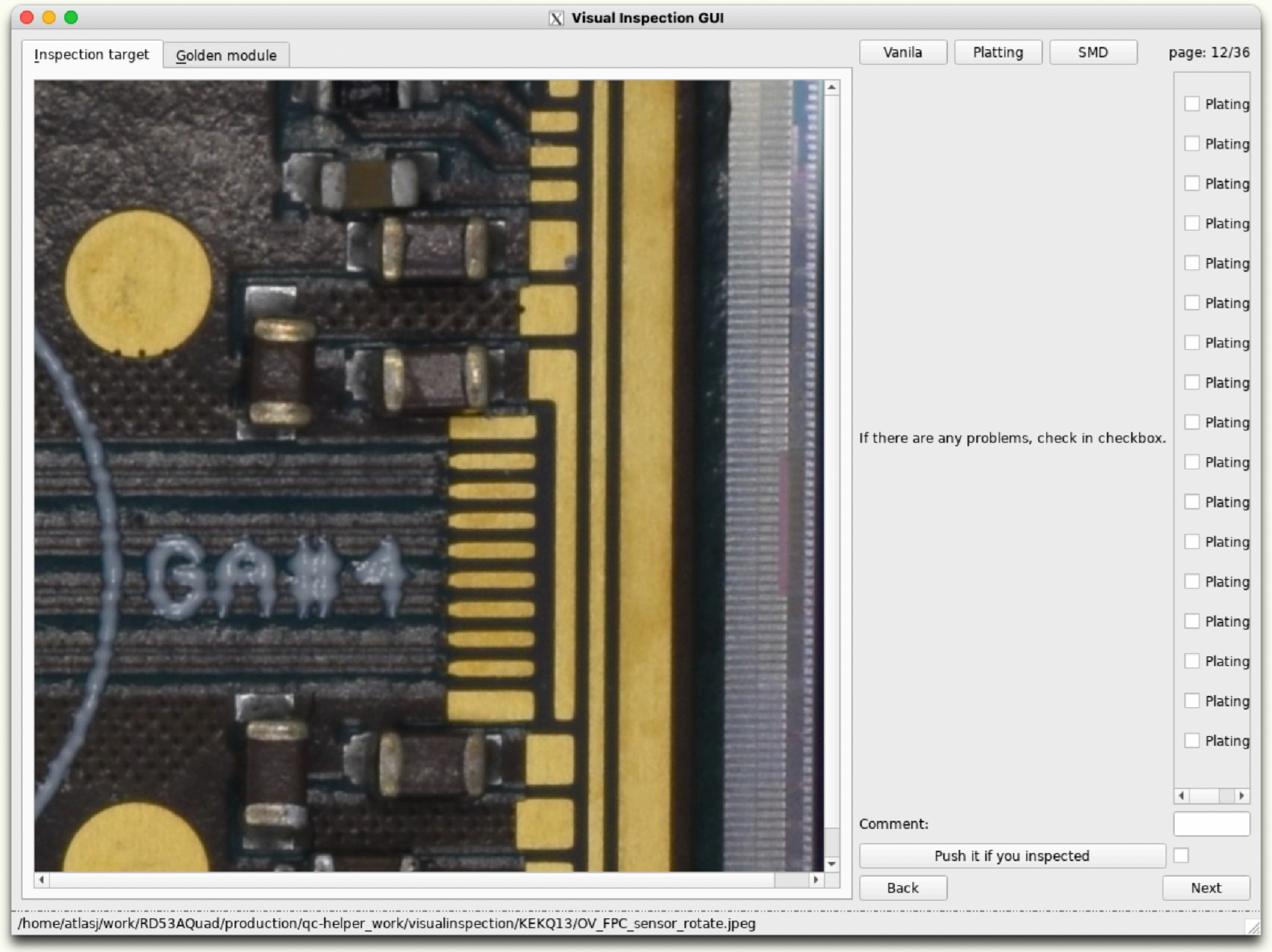
QC Helper

Data uploader for non-electrical tests





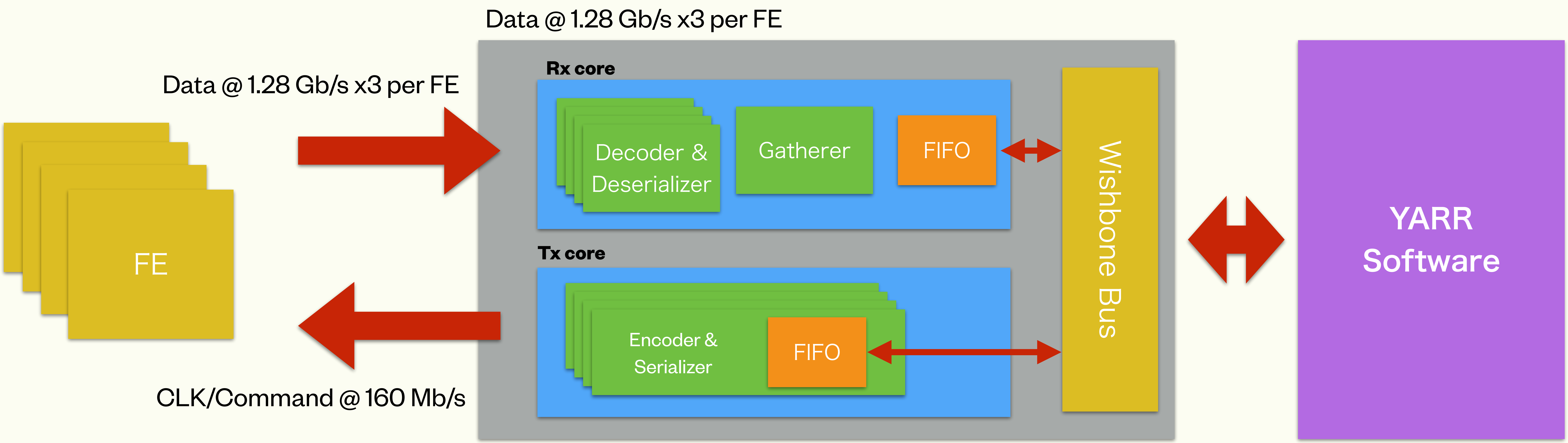




We're also trying to automatize visual inspection...

YARR - DAQ system

- PCIe based high-speed DAQ system
  - FPGA just aggregates data from FE ASICSs, everything sophisticated is done by its corresponding software



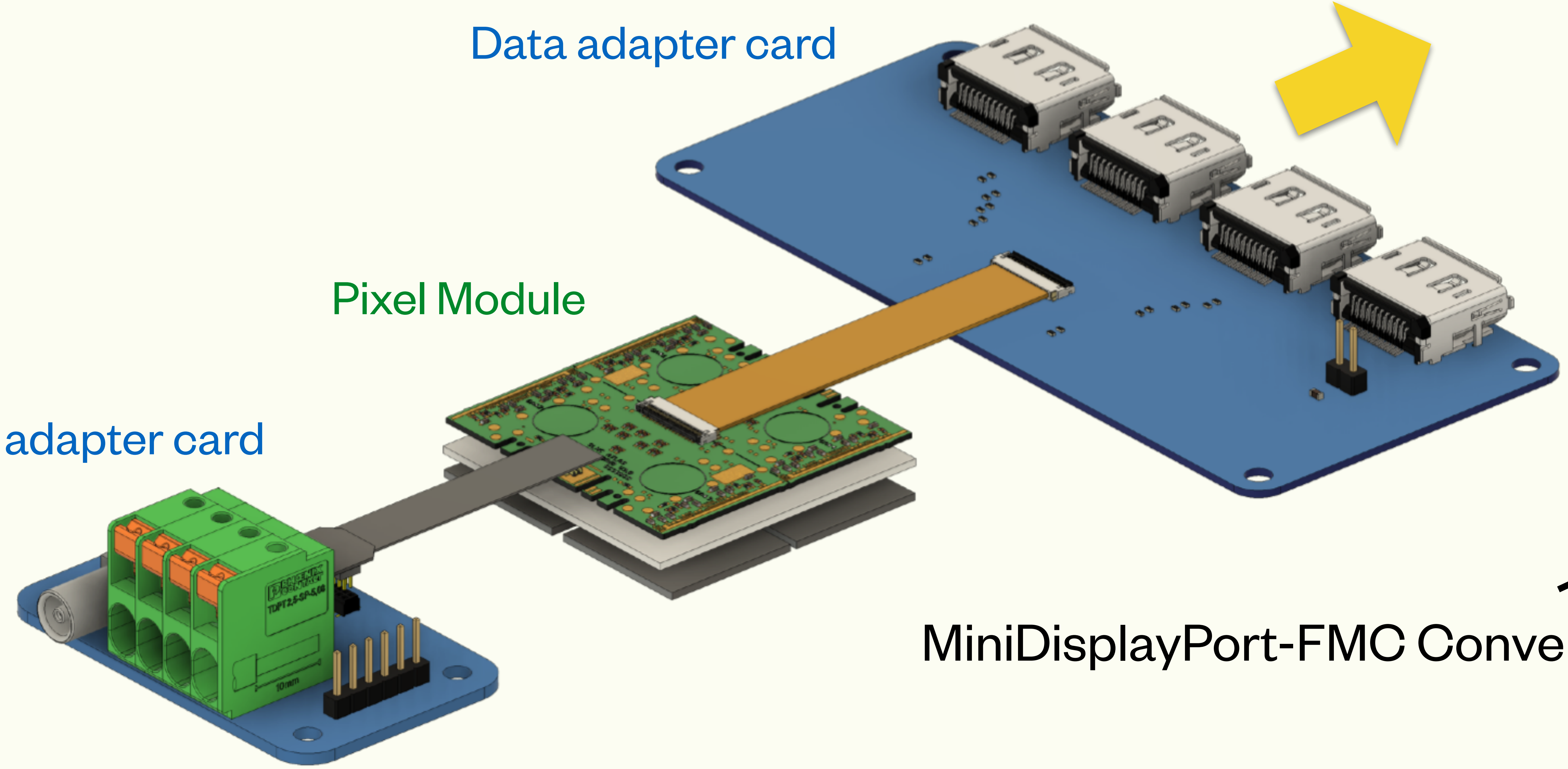
RD53A Testing Setup

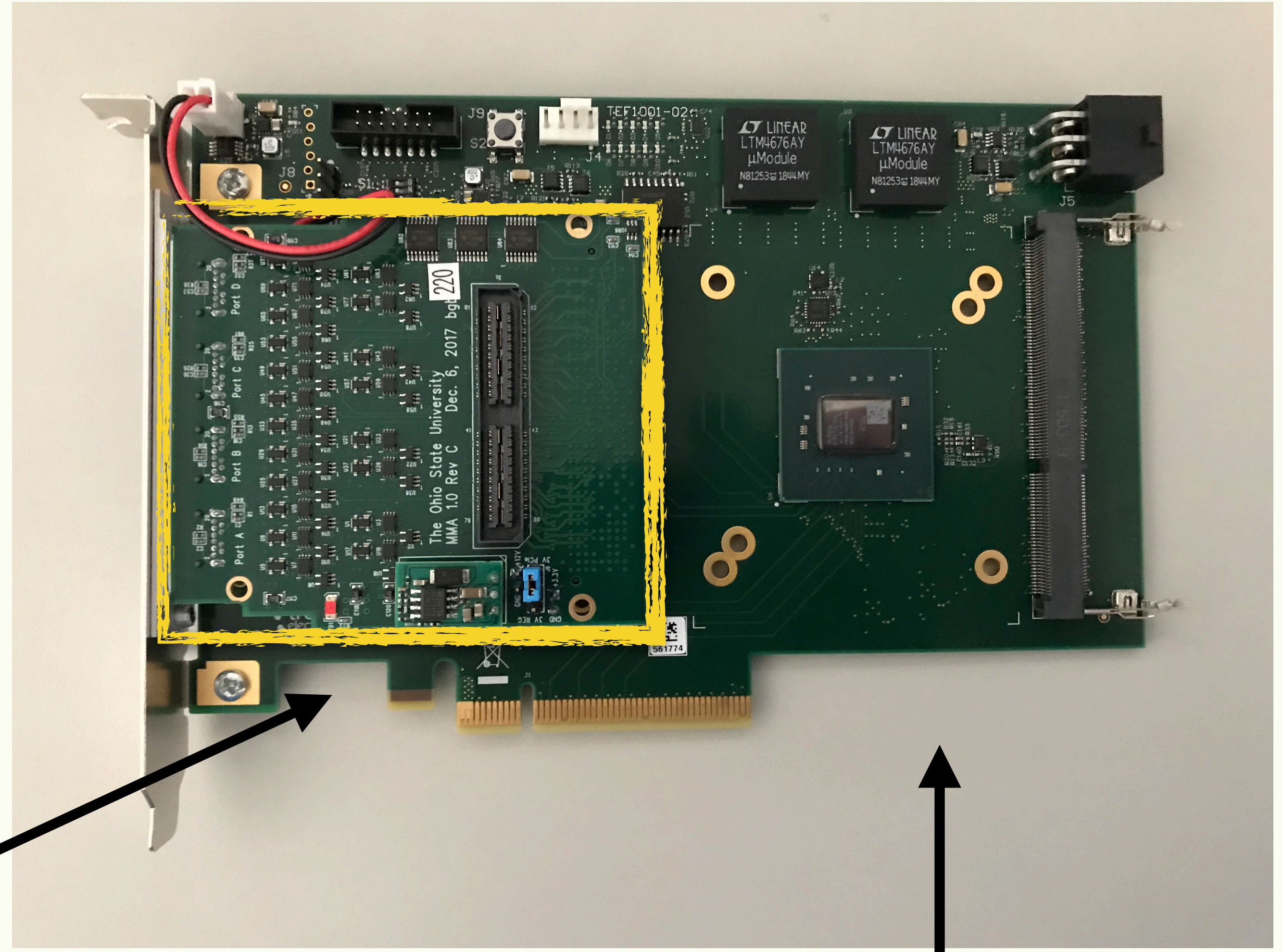
Data @ 1.28 Gb/s/lane

Data adapter card

Pixel Module

Power adapter card



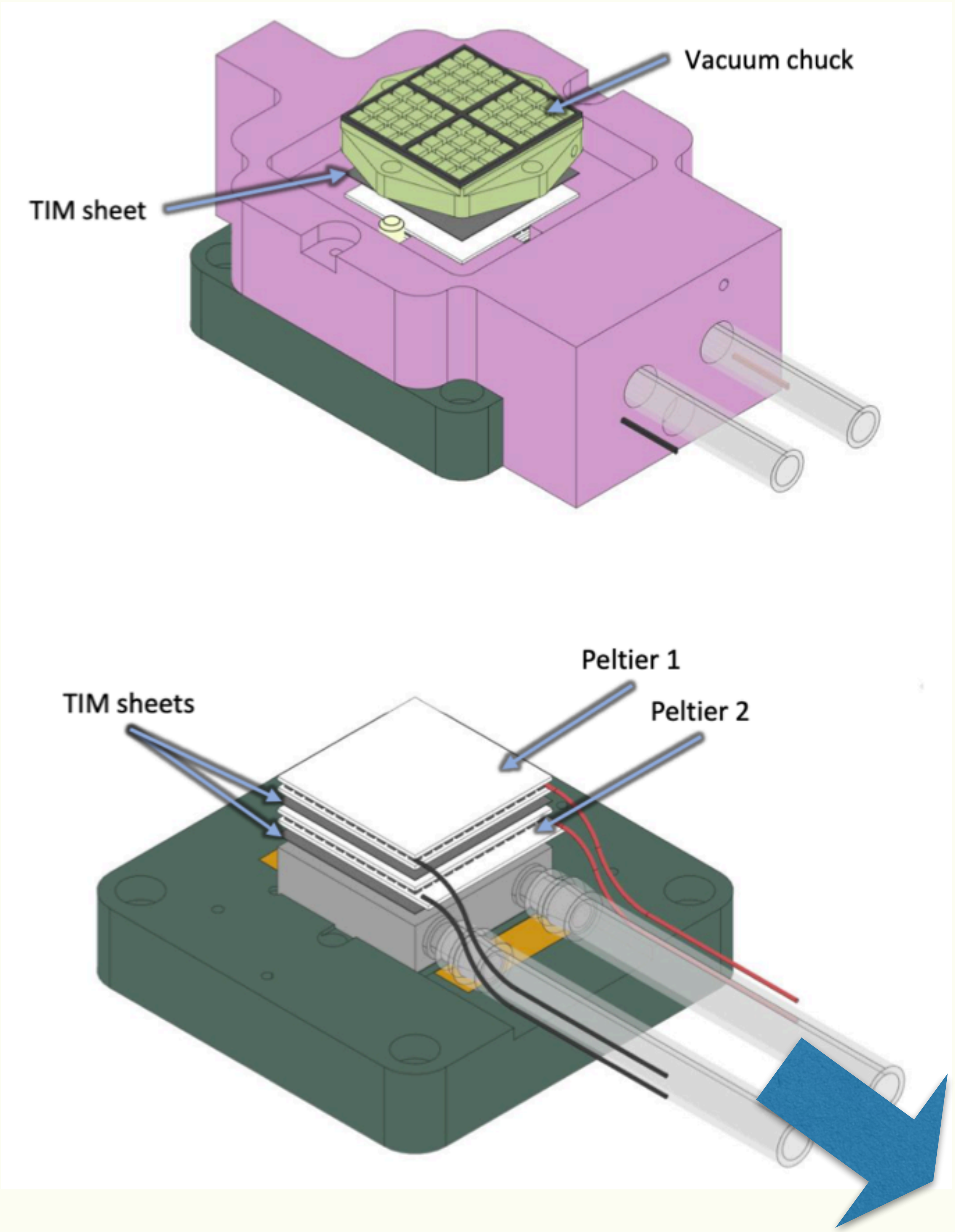


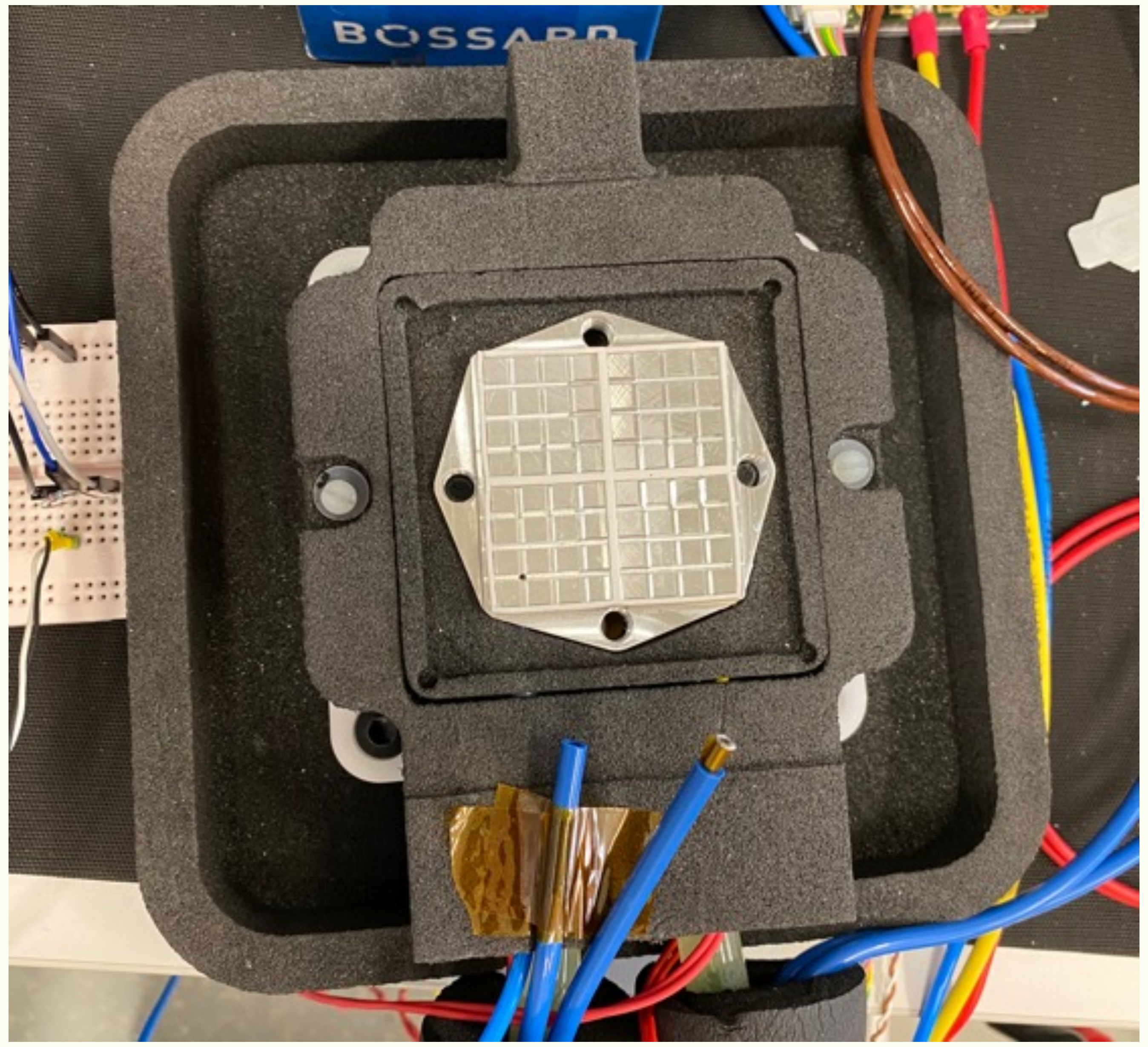
MiniDisplayPort-FMC Conversion

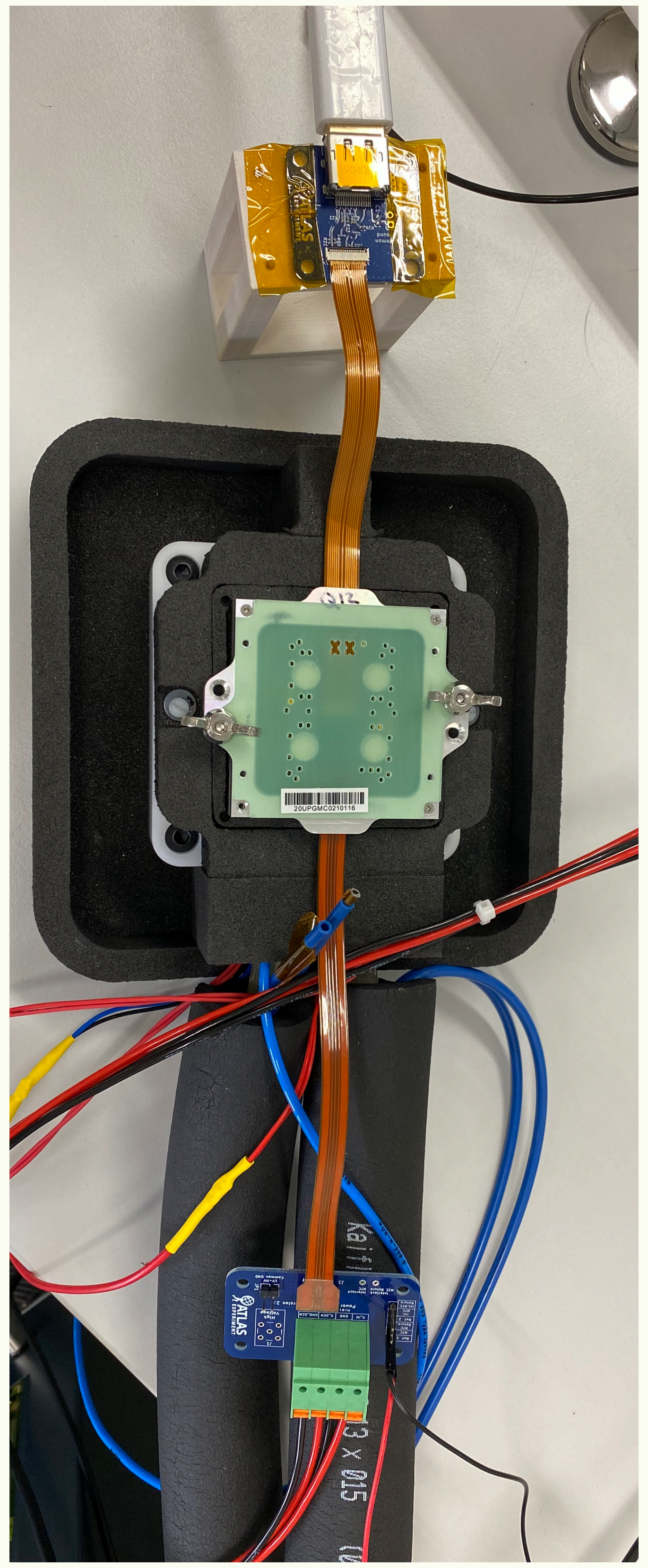
Trenz TEF1001 R2 FPGA Board

RD53A Testing Setup

Cooling system for the quad module



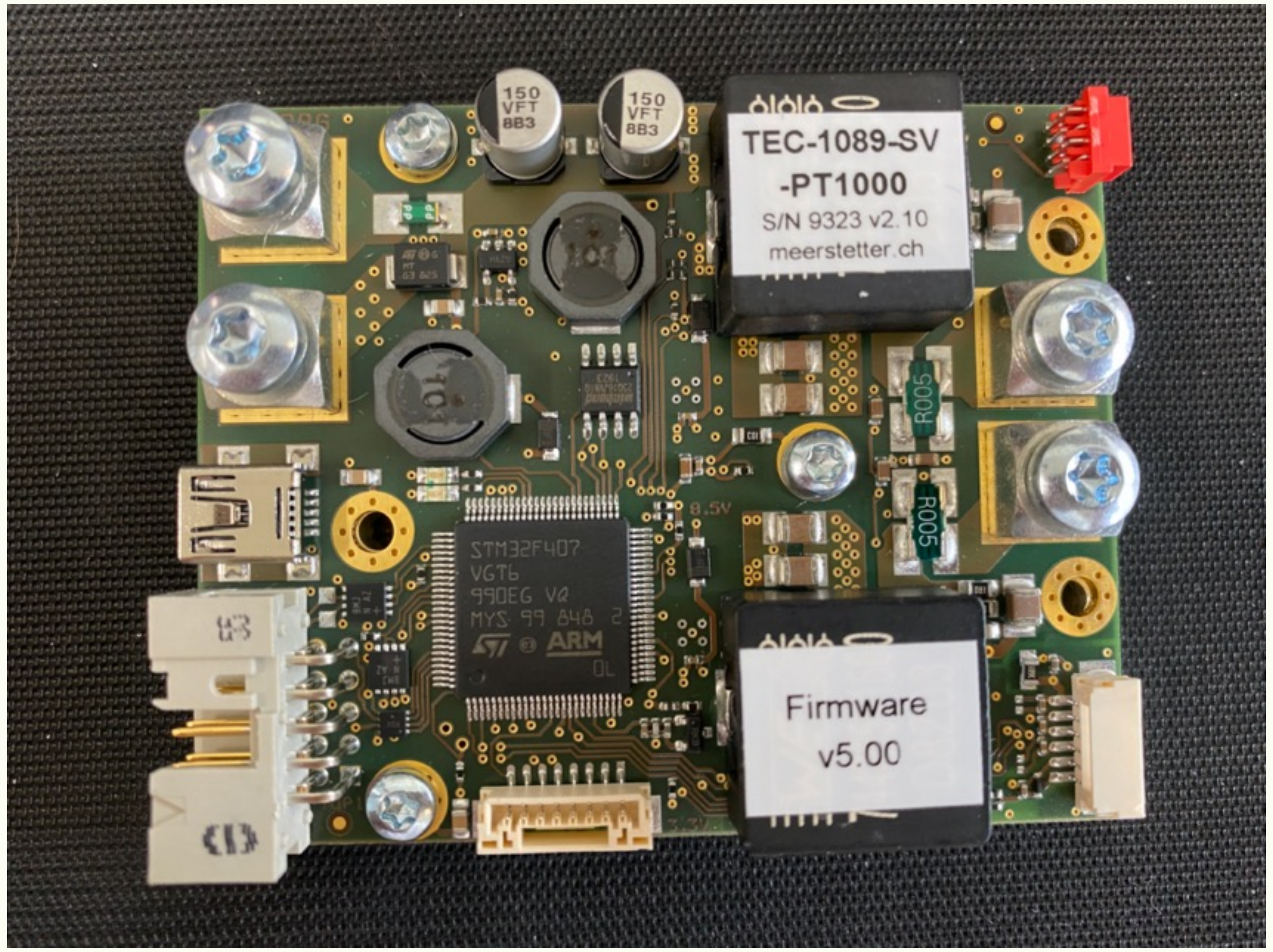




To Chiller

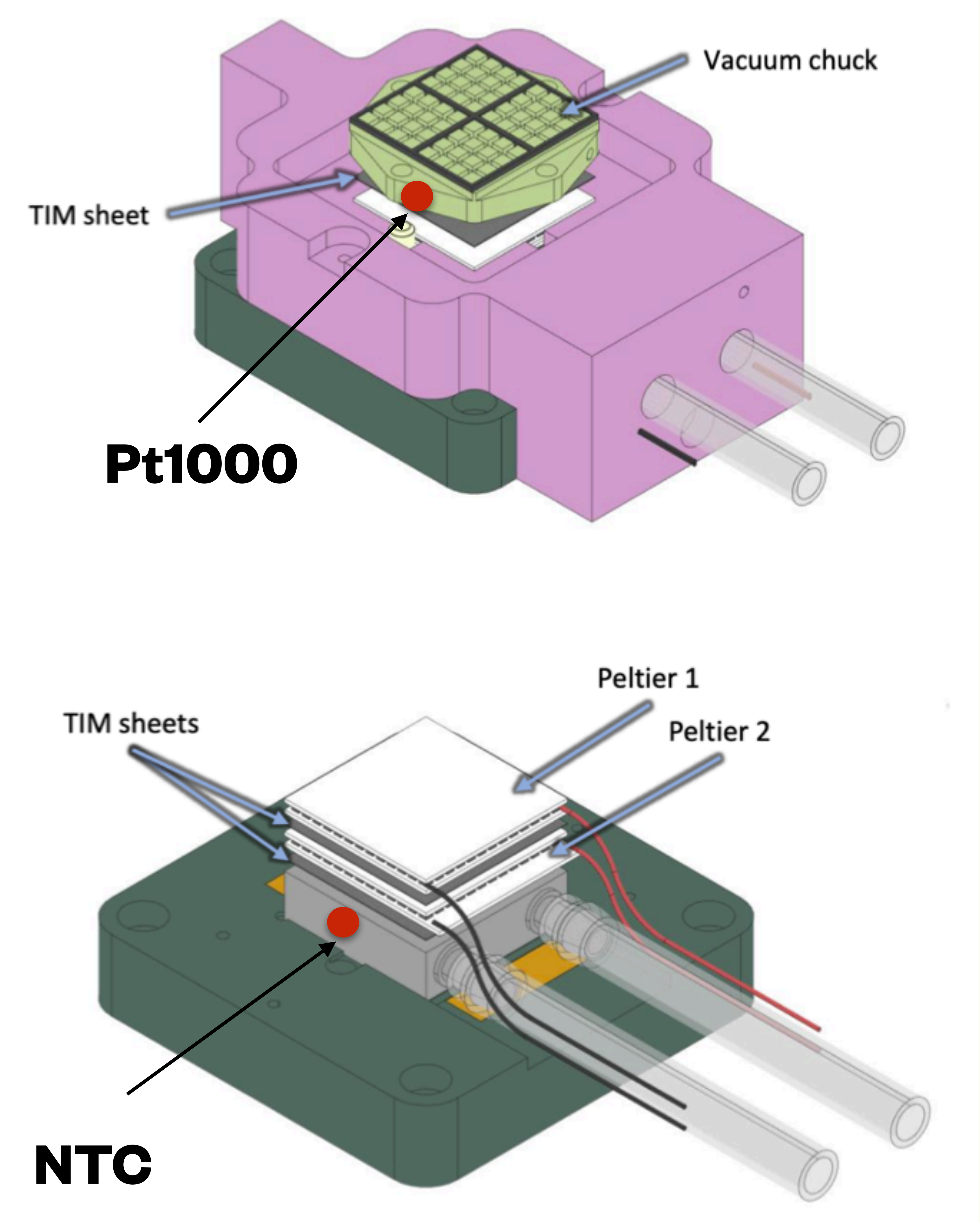
Peltier Control and Temperature Monitoring

TEC-1089-SC-PT1000

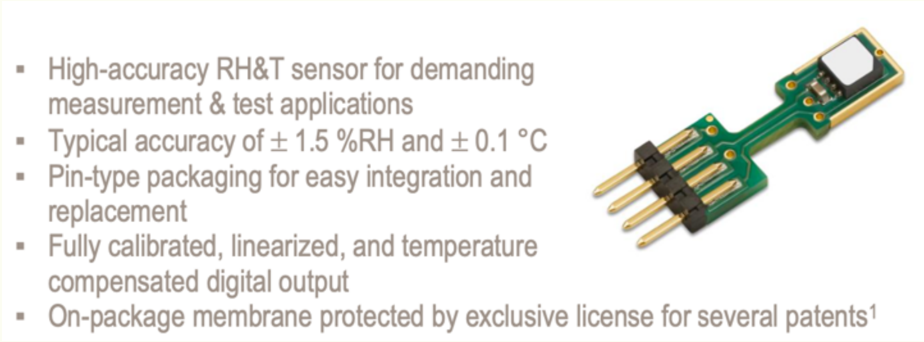


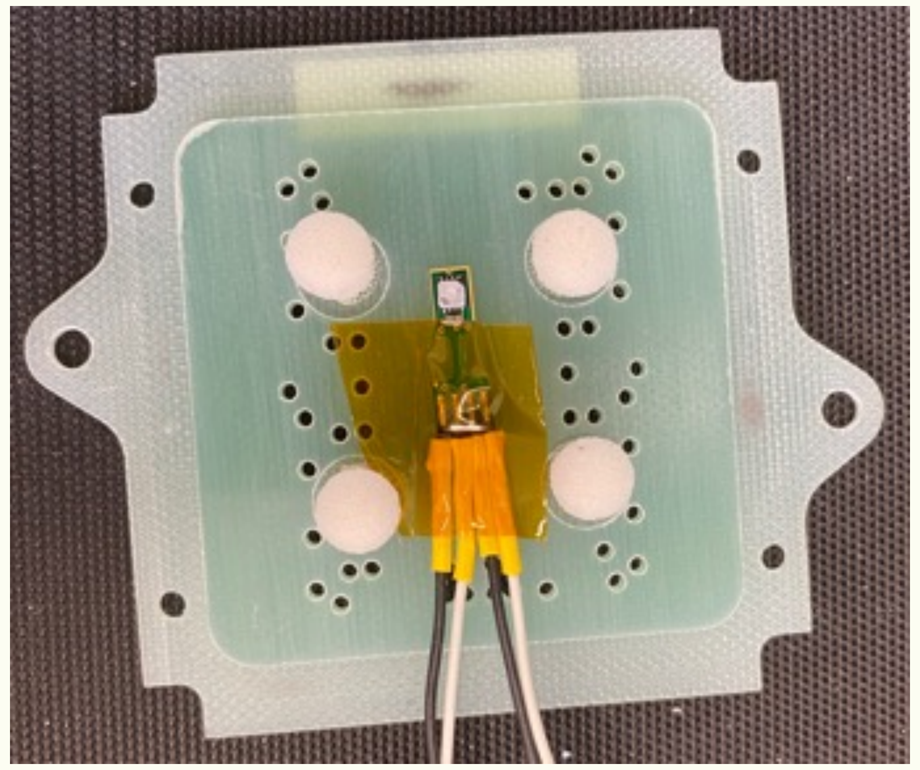
PID Control

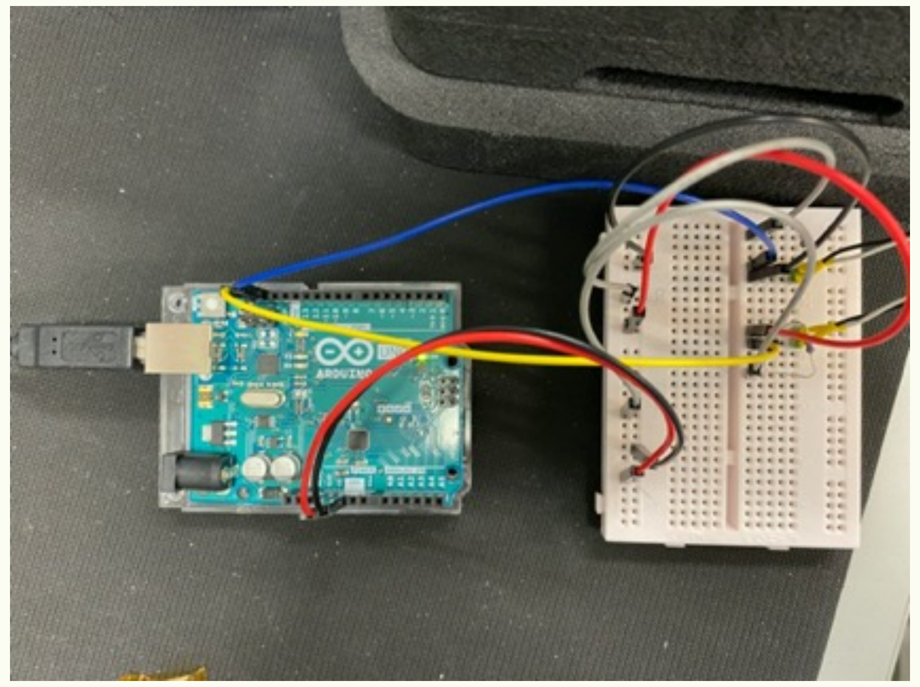
- Two temperature sensors as references
  - PT1000 for vacuum chuck
  - NTC for cold plate



SHT85

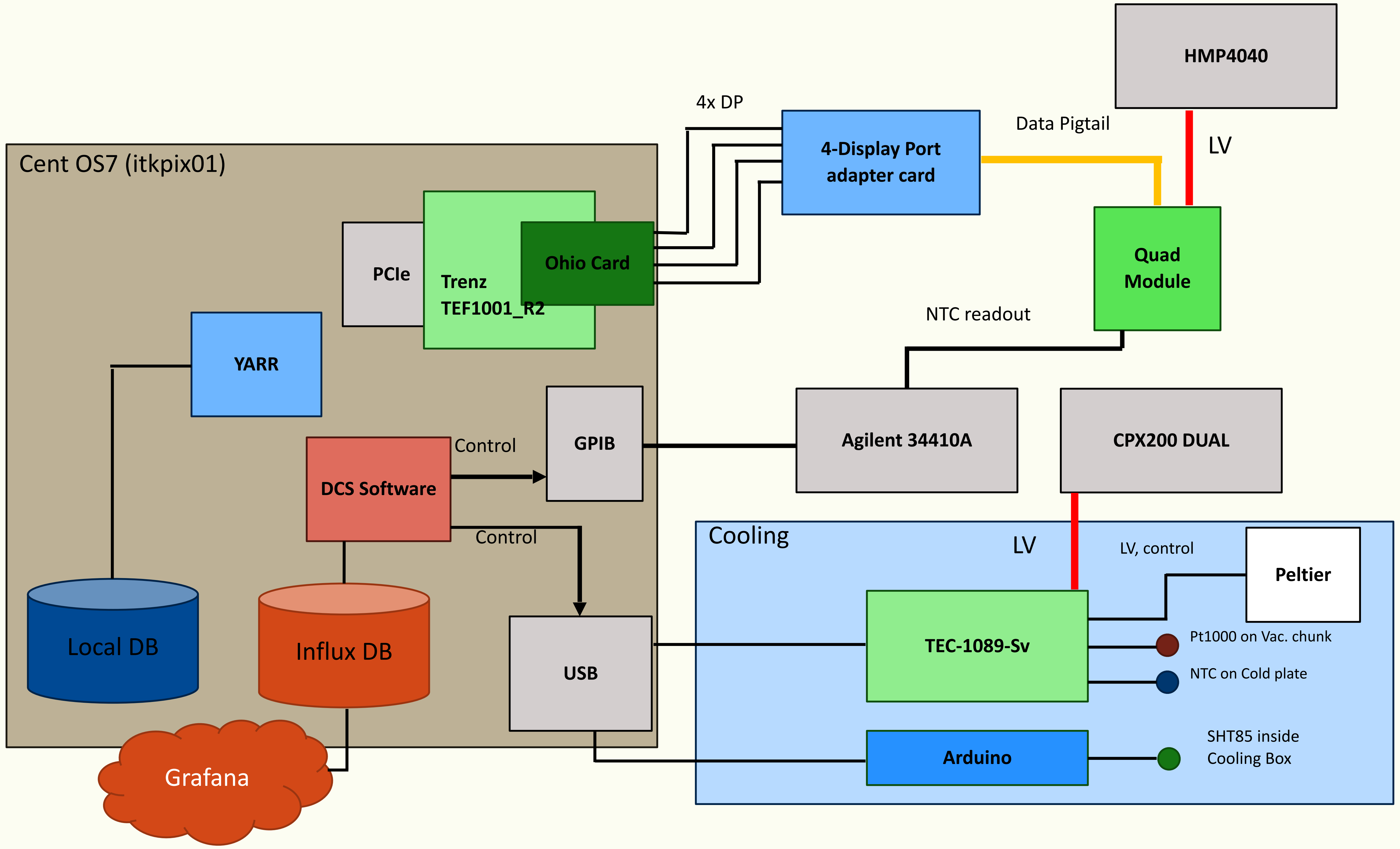




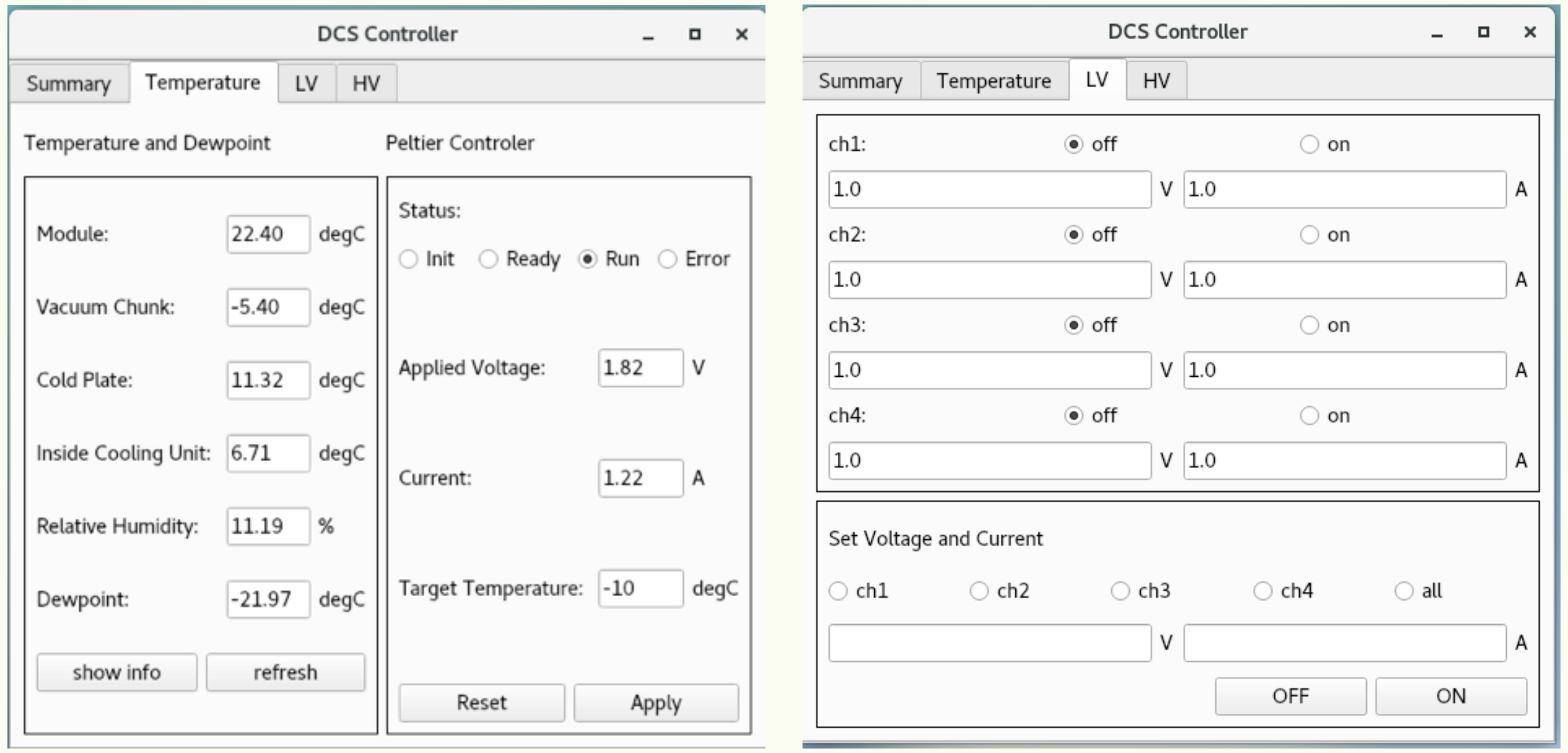


Temperature Control and Monitoring

Overview of testing setup @ UniGe

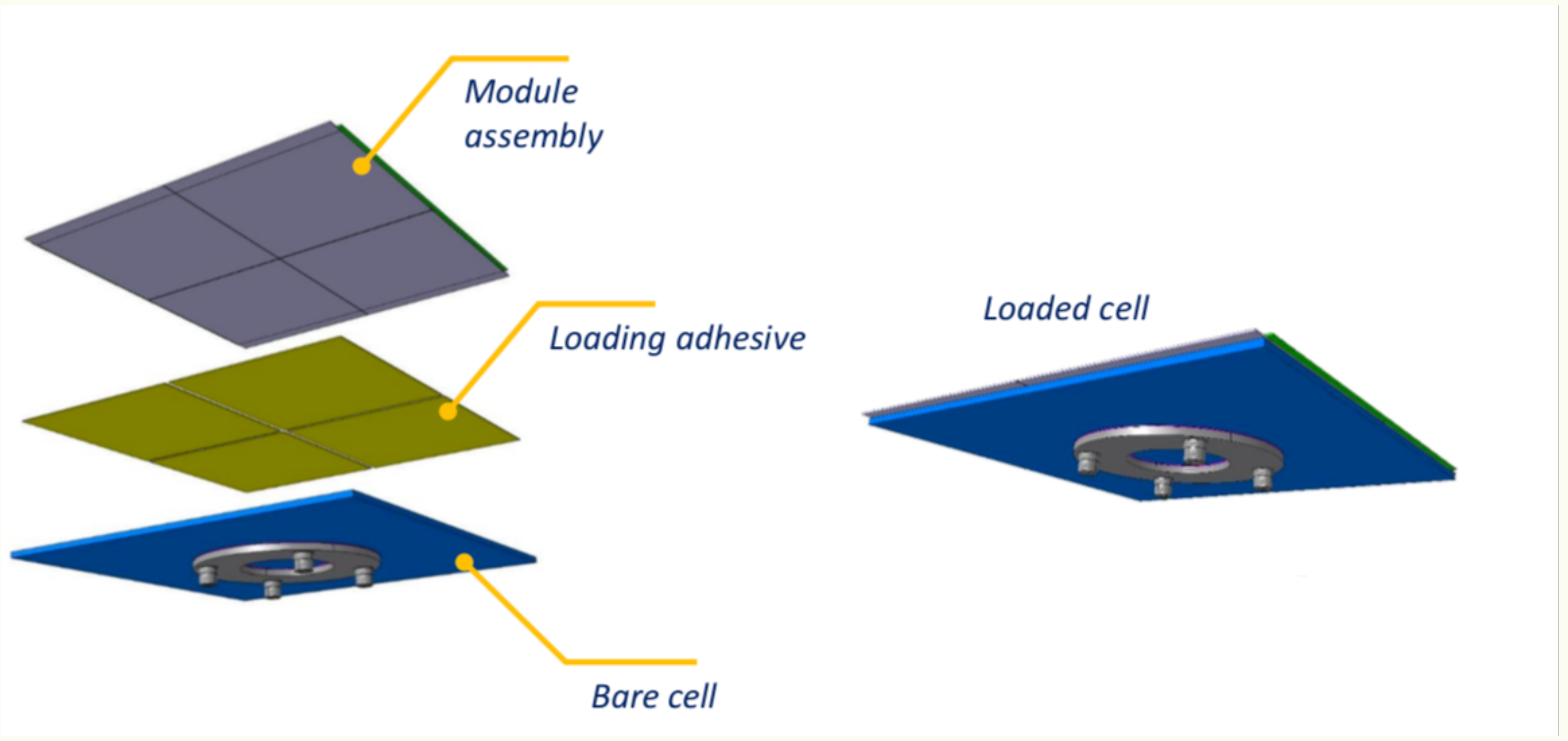


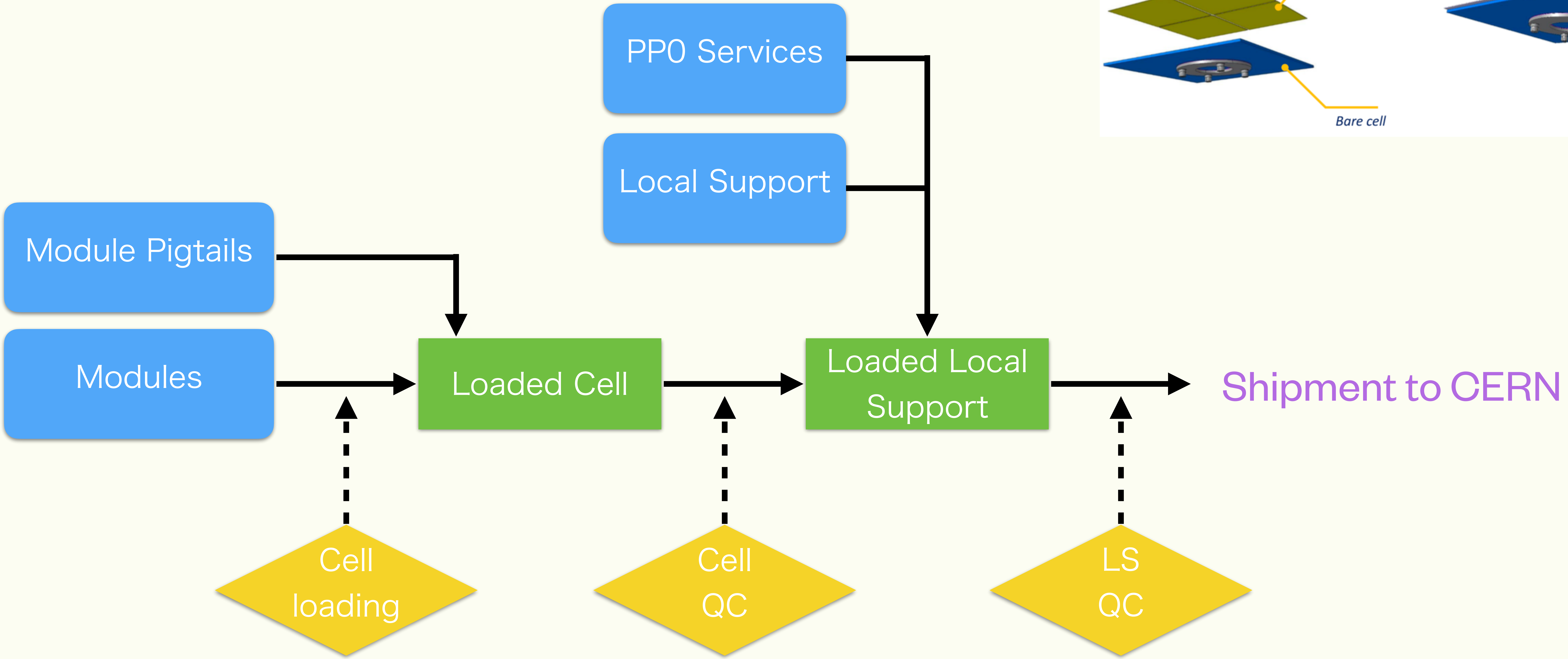
Controlled by GUI



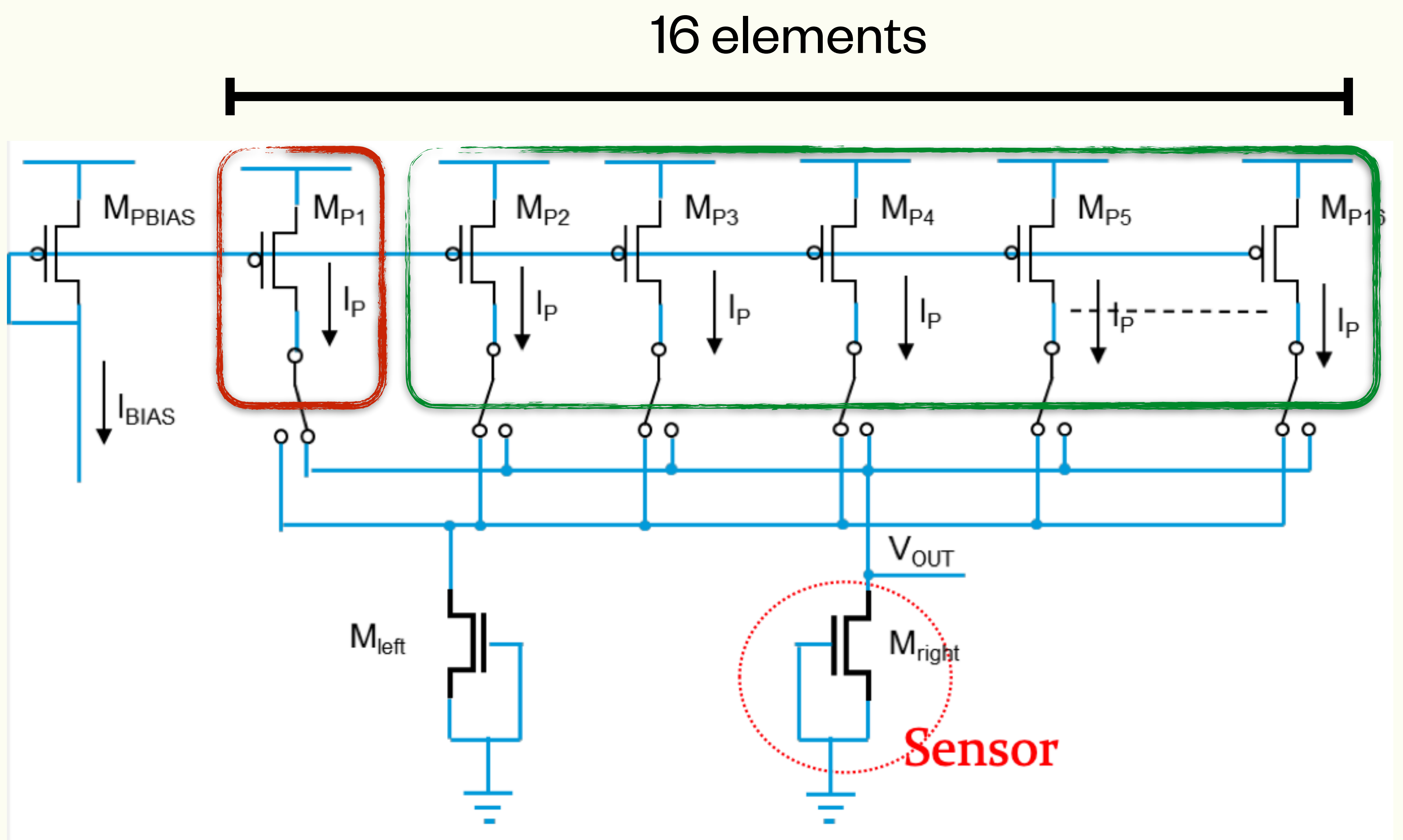
Monitored by Grafana (recorded in the influxDB)

Loaded Cell Module



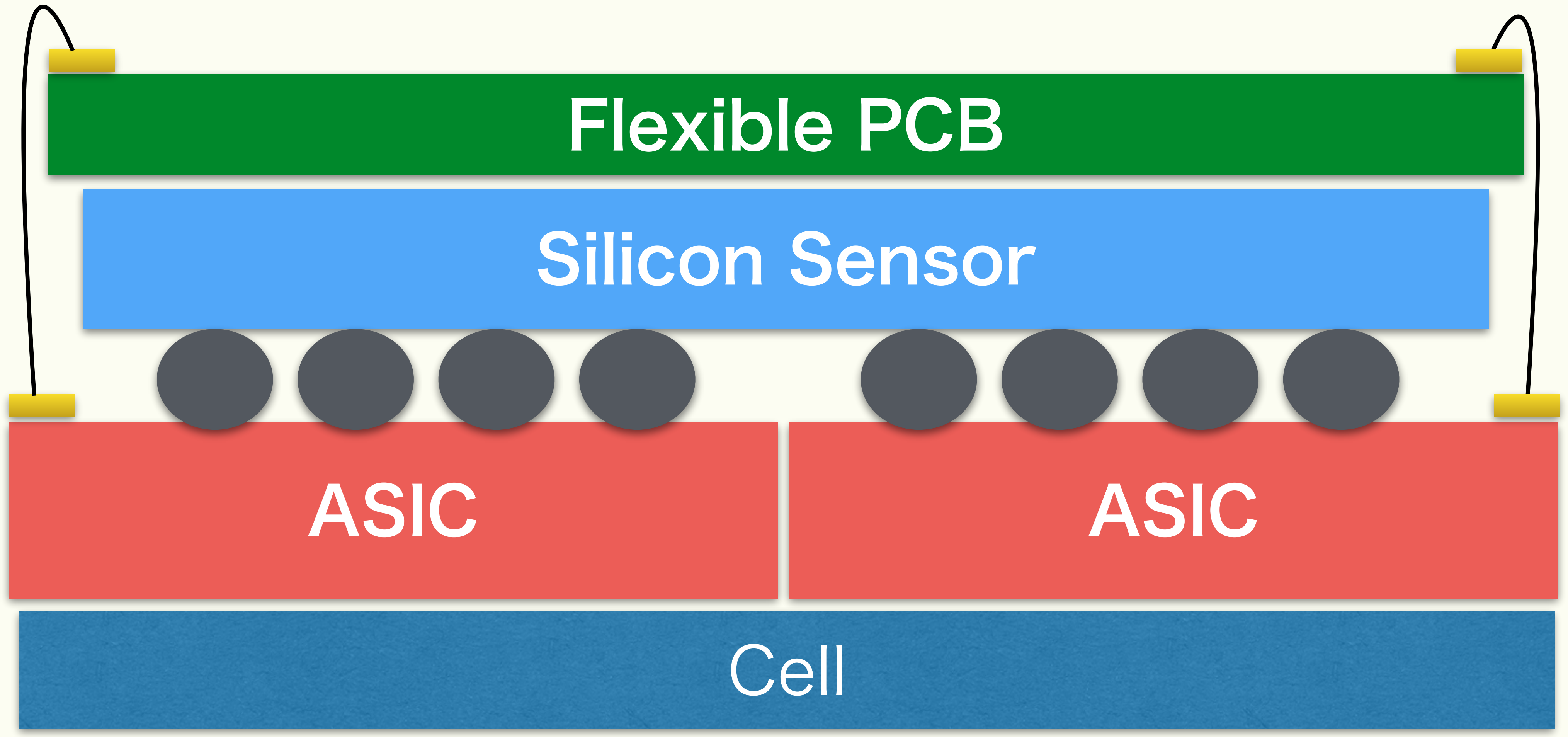


Module Temperature



Temperature Sensors of the Module

- 2 NTCs on the PCB
- 4 NMOS temperature sensors in each ASIC
  ➡ These sensors are available only when chip turns on



$$\Delta V = N_f \times \frac{kT}{q} \times \ln R$$

$V_1 = \mathrm{M}_{\mathrm{right}}$ Biased at 1 x I_p

$V_2 = \mathrm{M}_{\mathrm{right}}$ Biased at 15 x I_p

$$\Delta V = V_2 - V_1$$

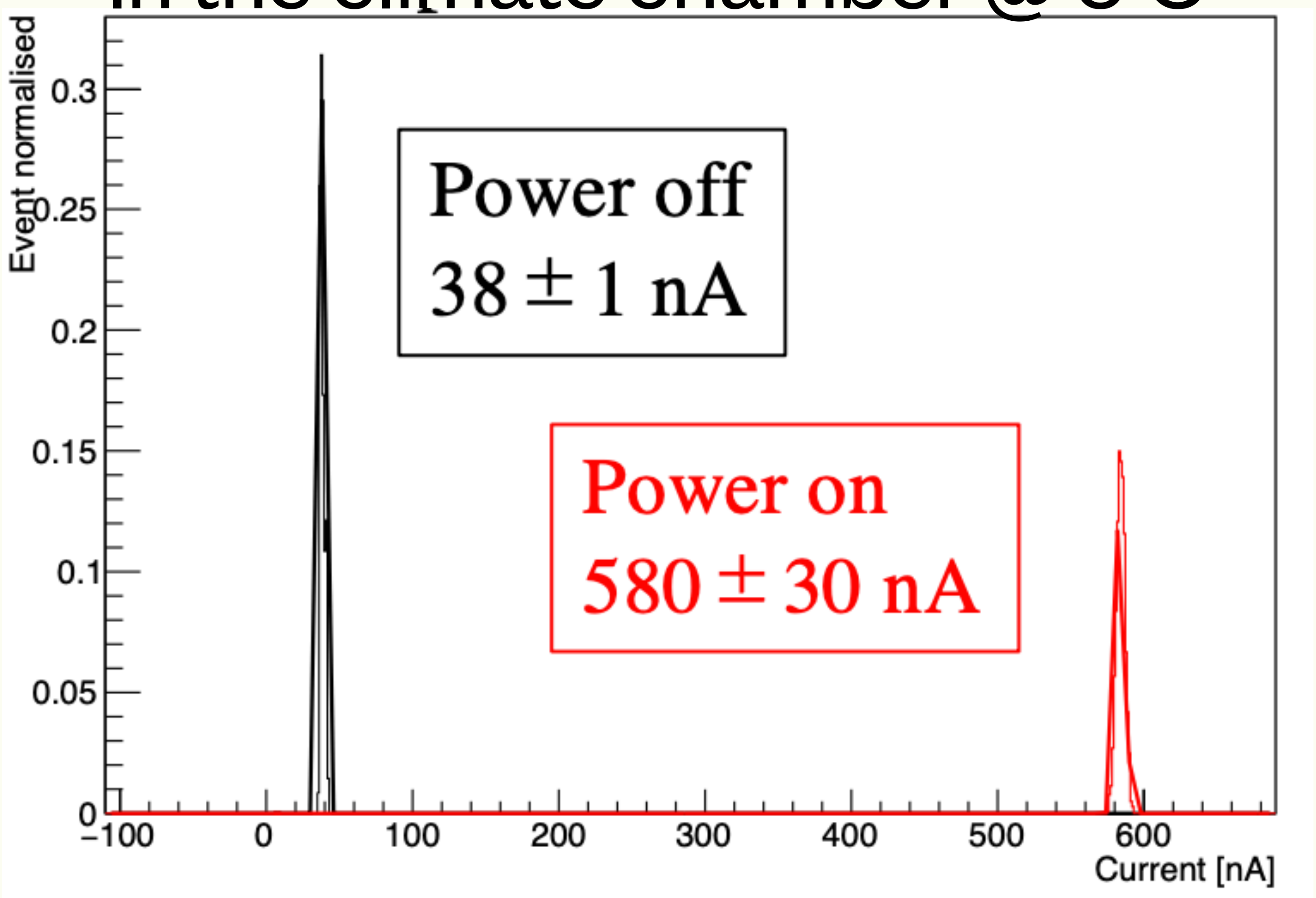
How to calibrate temperature sensors in the ASIC?

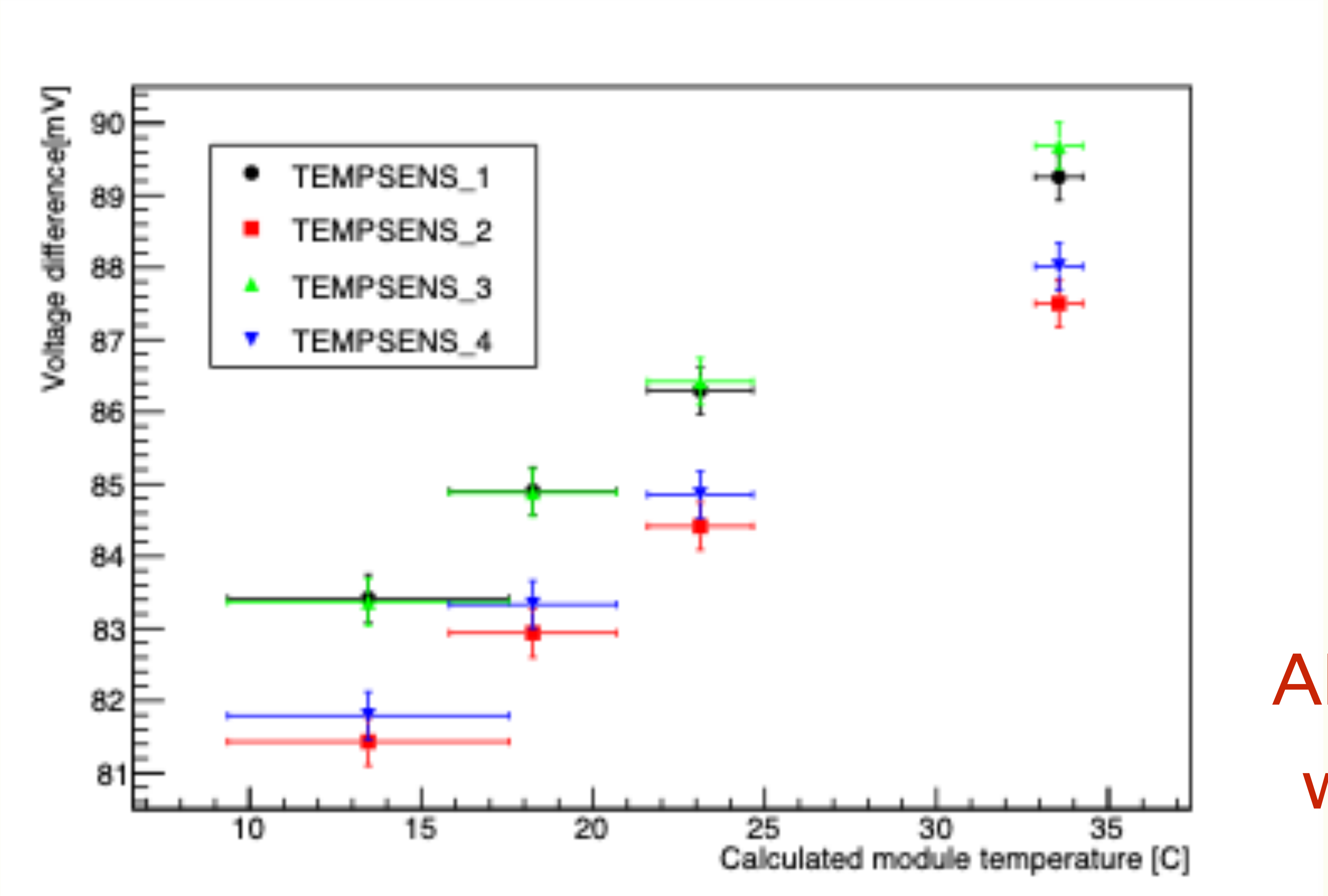
Temperature Sensor Calibration

Leakage current of a silicon sensor depends on its temperature

$$\frac{I(T_2)}{I(T_1)} = \left(\frac{T_2}{T_1}\right)^2 e^{-\frac{E_g(T_2)}{2kT_2}+\frac{E_g(T_1)}{2kT_1}}, E_g(T) = E_g(0) - \frac{\alpha T^2}{T+\beta}$$

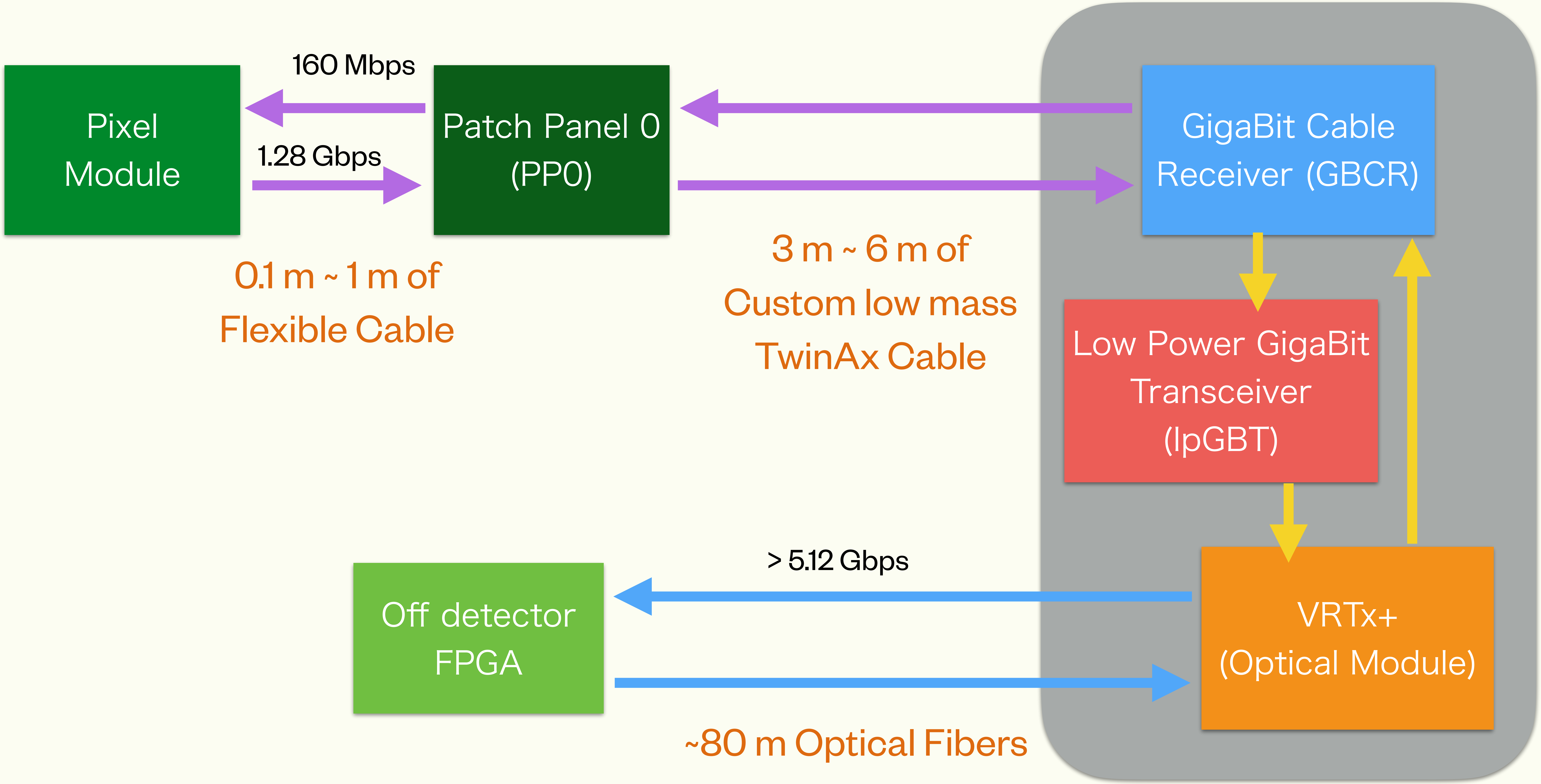
In the climate chamber @ 0 C





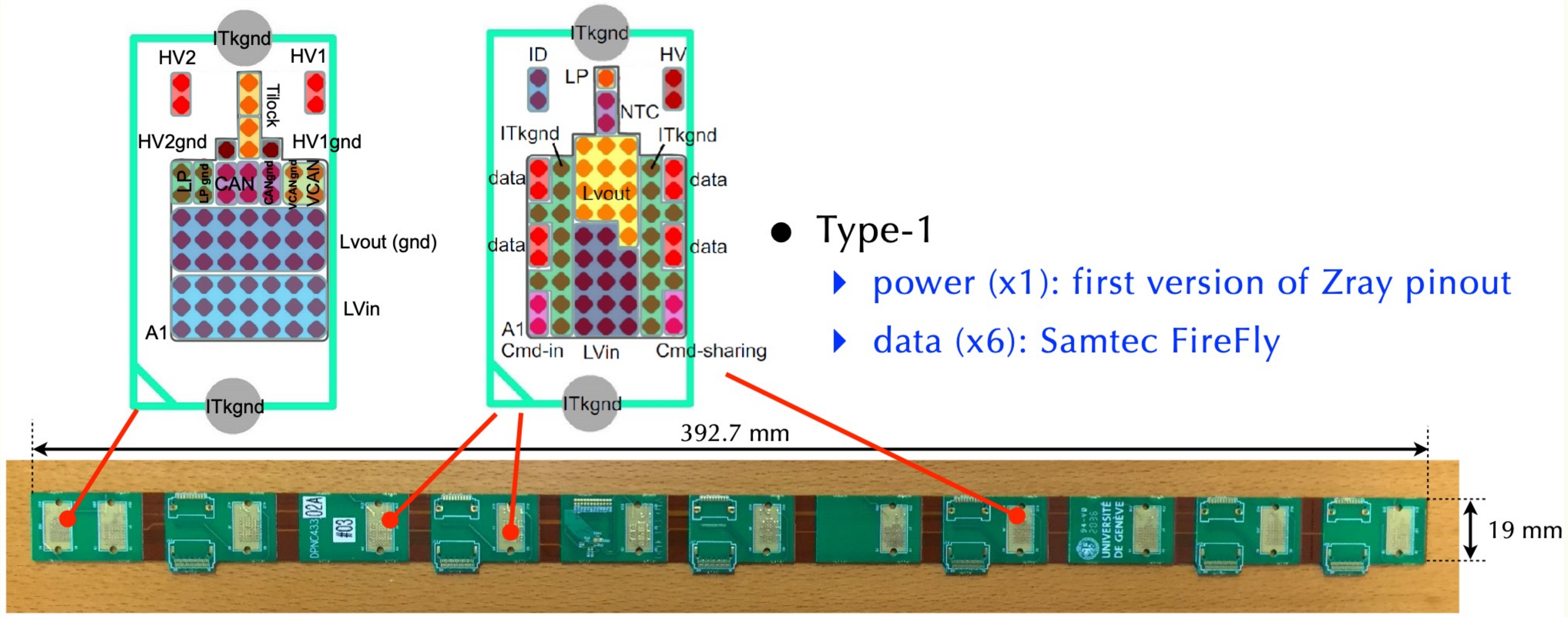
Able to calibrate each sensor with the accuracy of ± 1.3 C

Upstream Data Transmission



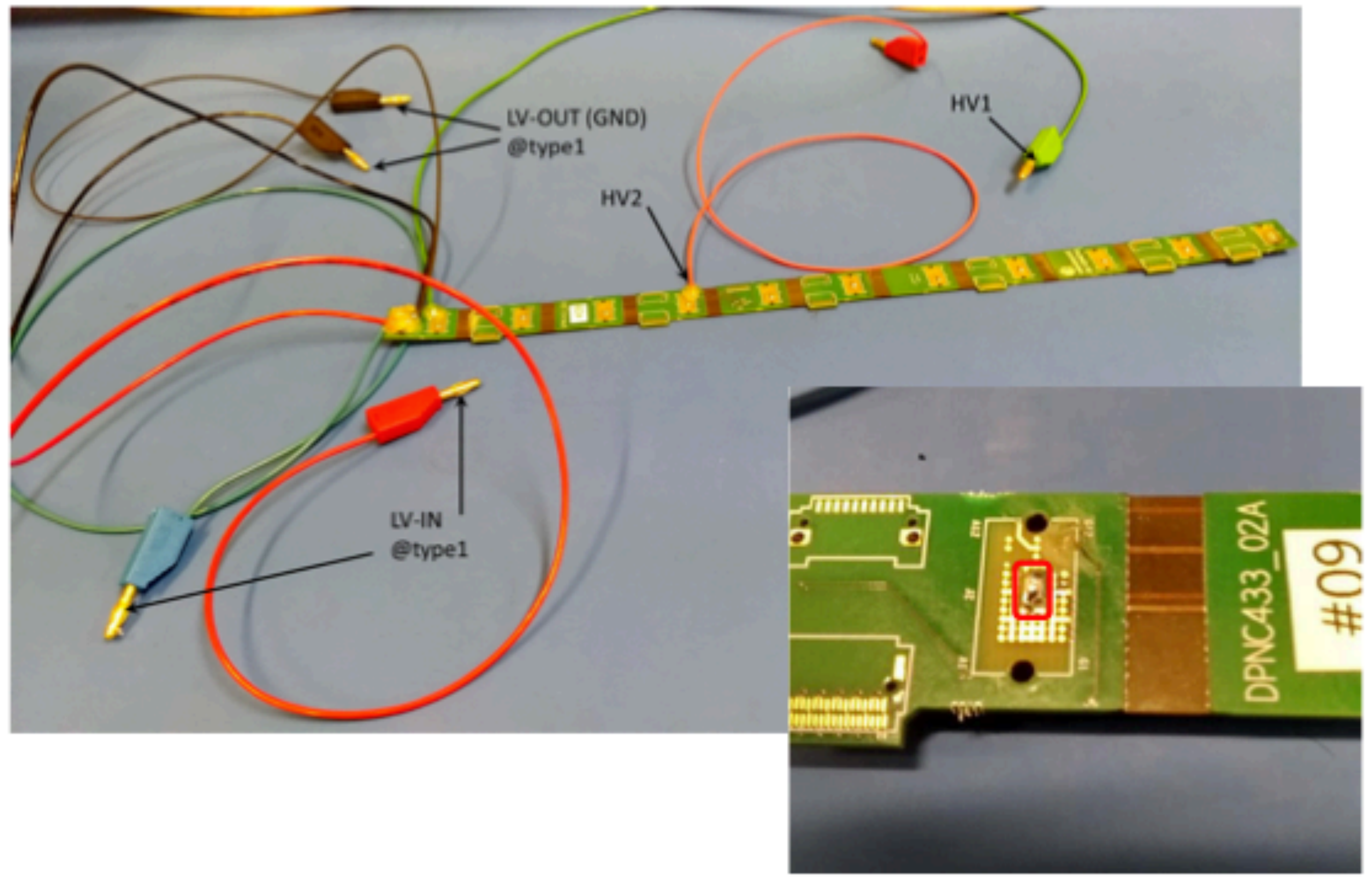
PP0 Prototype

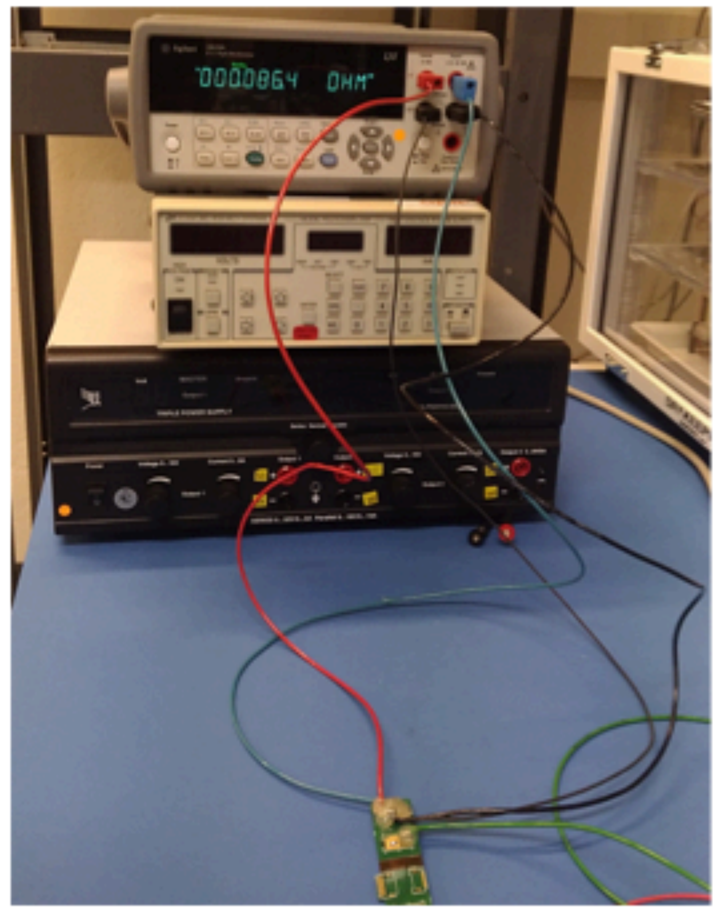
- First inclined PP0 prototype
  - based on design done for services PDR
  - Adapted from L4 to L3

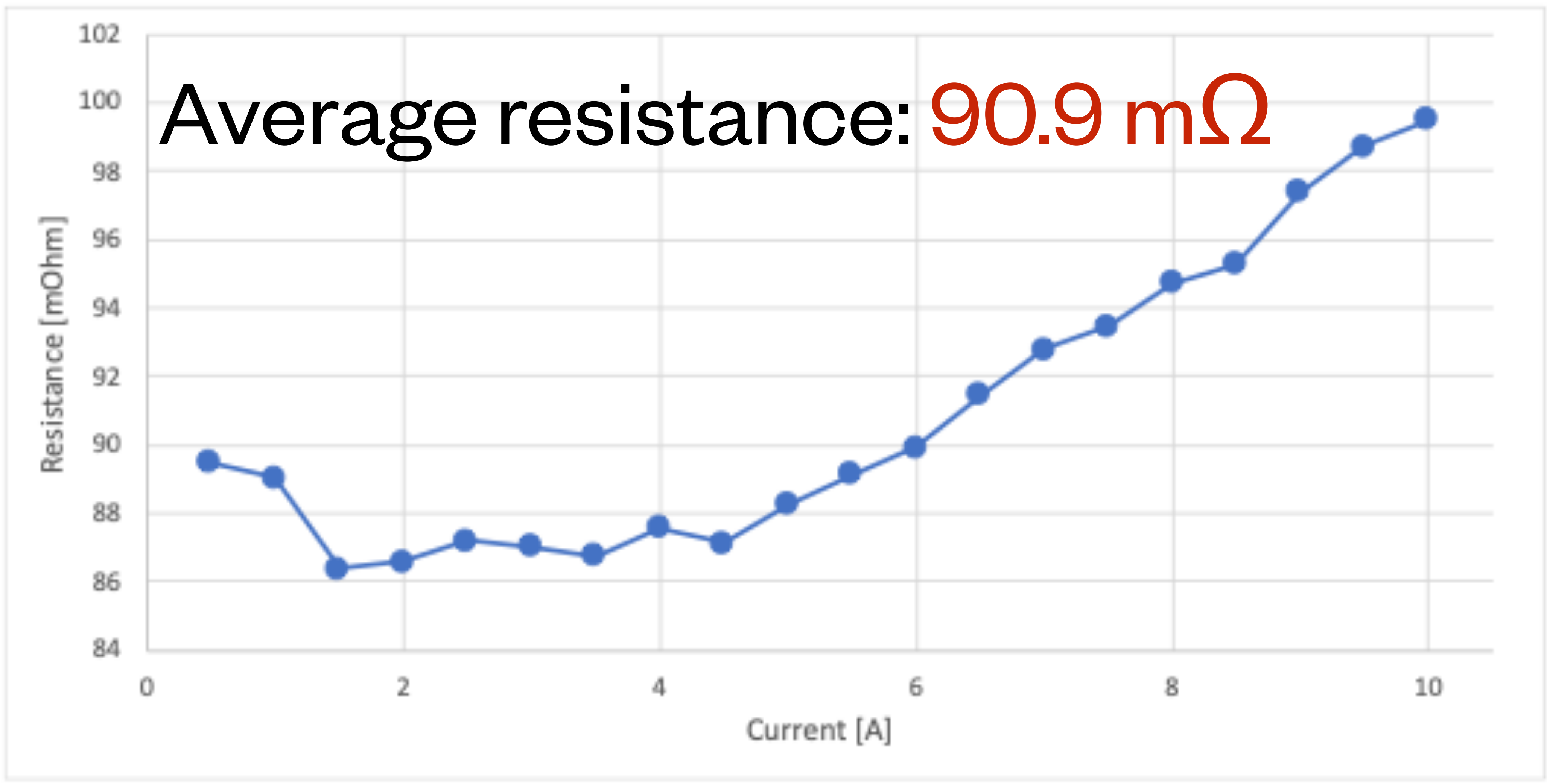


- Type-1
  - power (x1): first version of Zray pinout
  - data (x6): Samtec FireFly

LV round-trip resistance

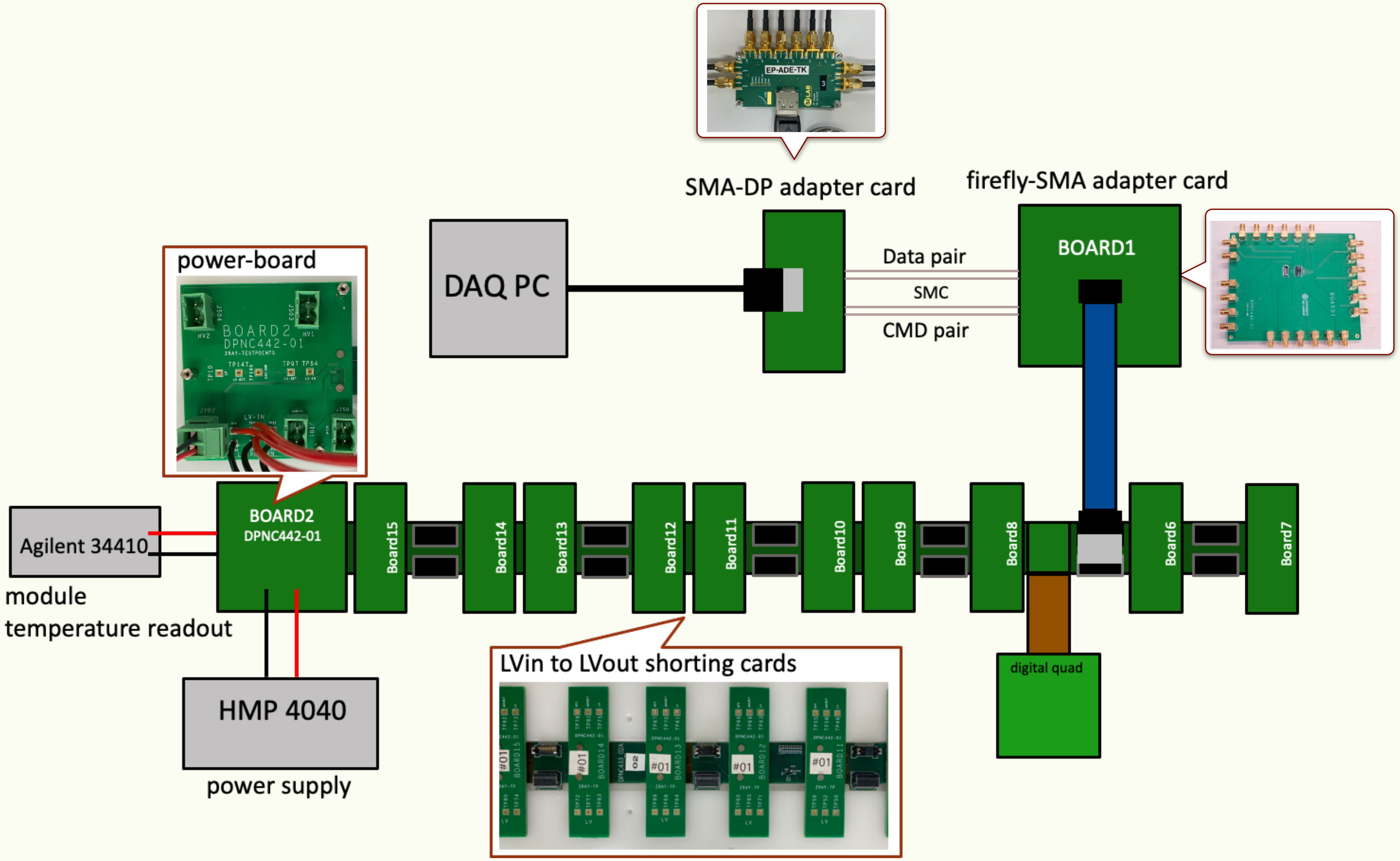


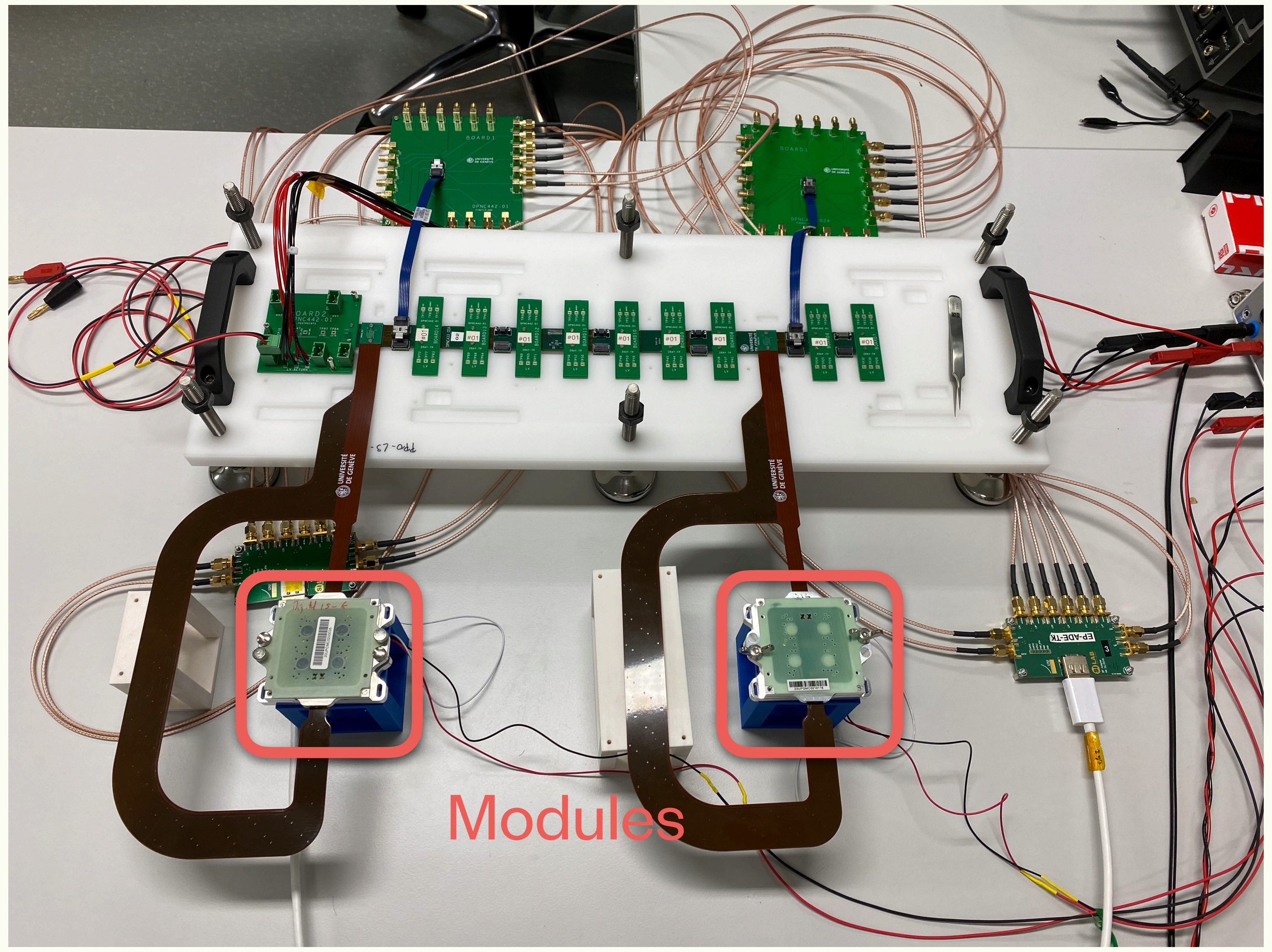




Readout Test for PP0 Prototype

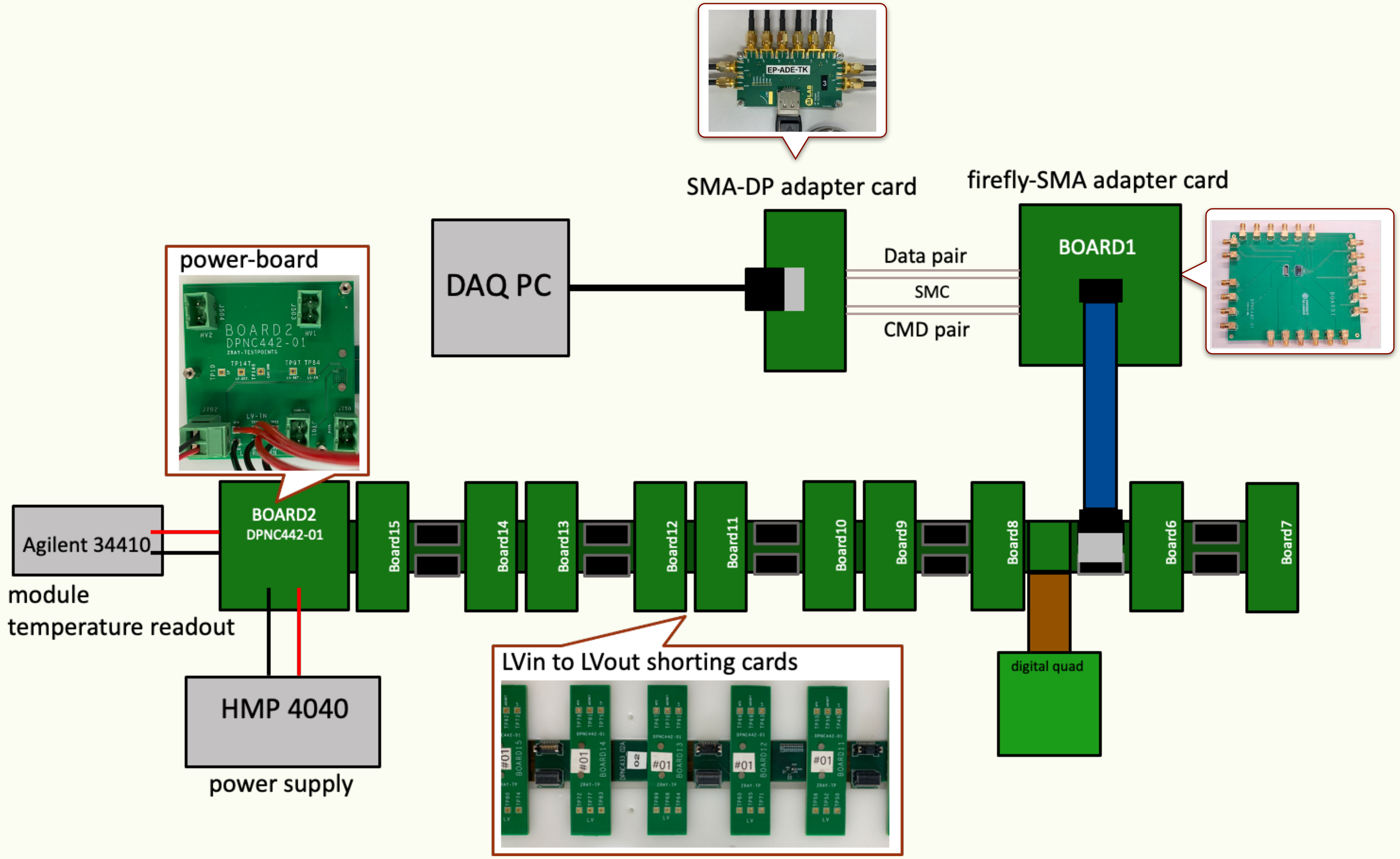
- Testing with 2 quad modules

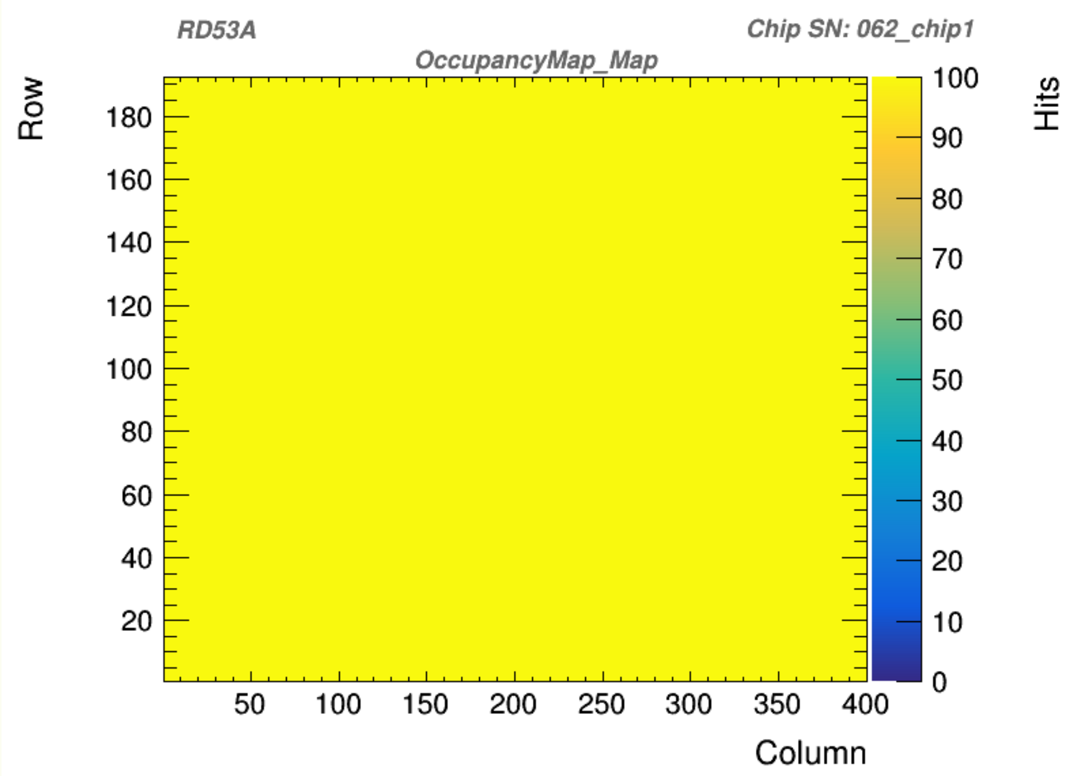


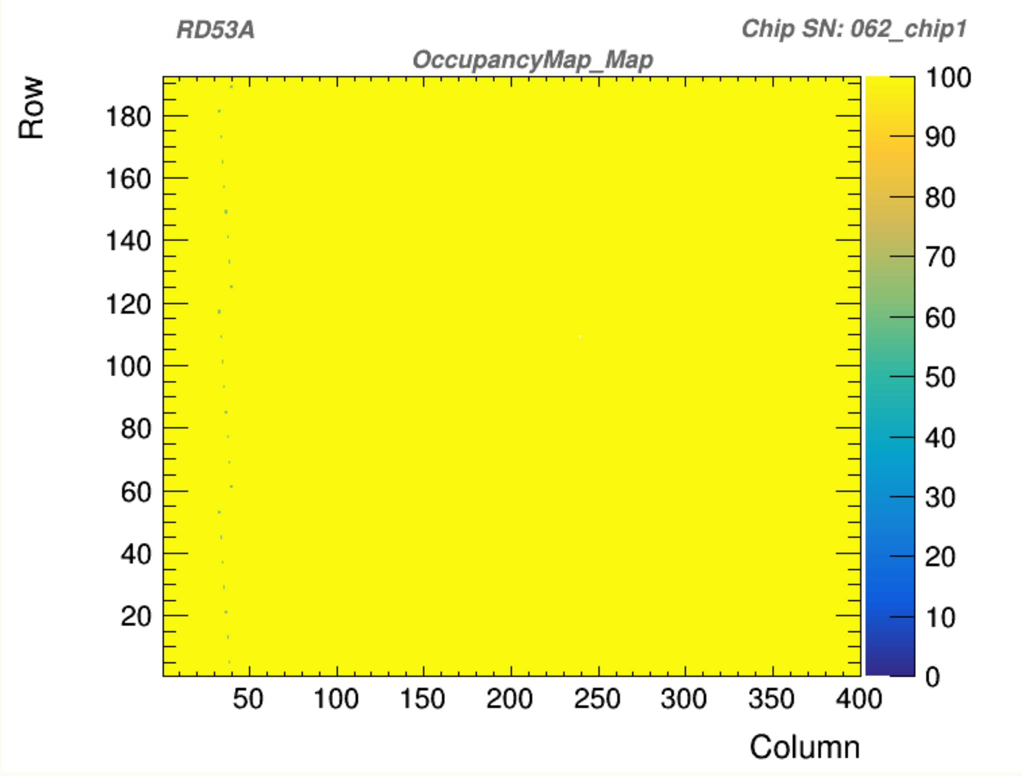


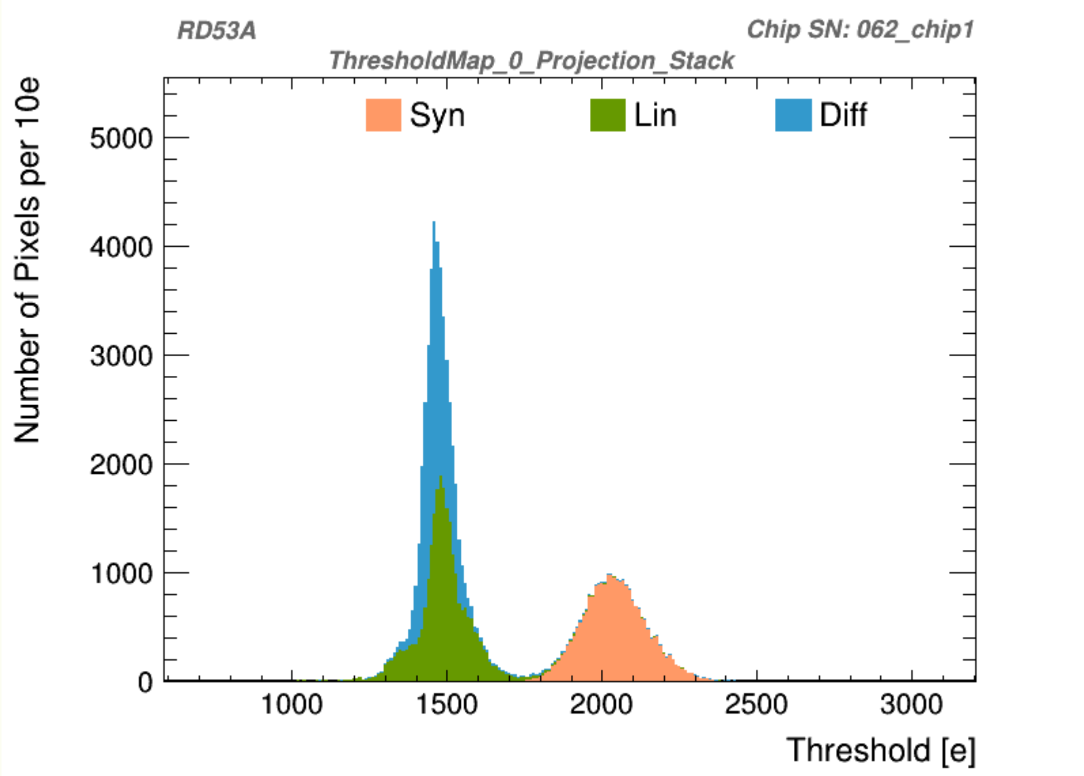
Readout Test for PP0 Prototype

- Testing with 2 quad modules









Get equivalent results as module stand alone test

Conclusion

- There are many activities toward Phase-II ATLAS ITk Upgrade
  - Preparing for the mass production of Pixel detector
  - Testing setup, procedure, database, and so on…
- Real production phase is approaching!!

Thank you for your attention!!

ご清聴有り難うございました。