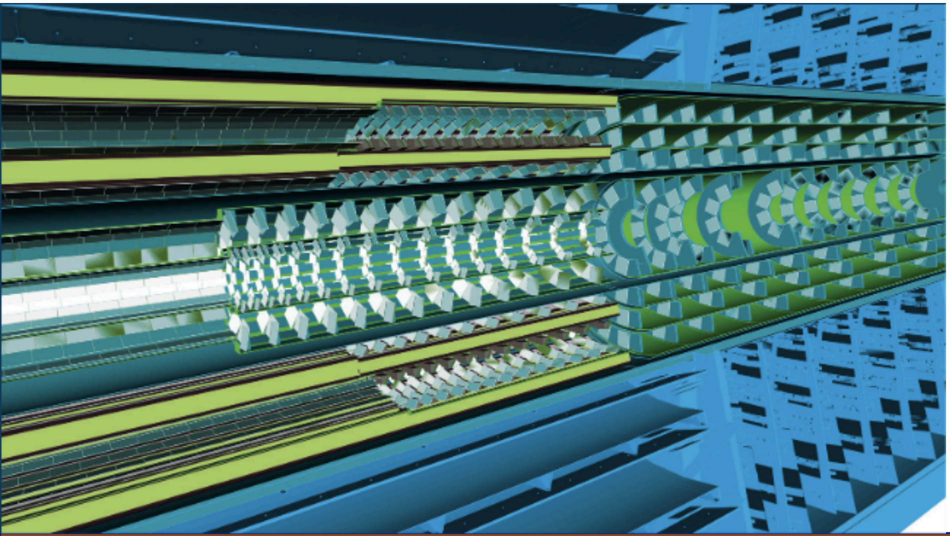
ATLAS ITk Pixel Detector Overview



Attilio Andreazza

Università di Milano and INFN

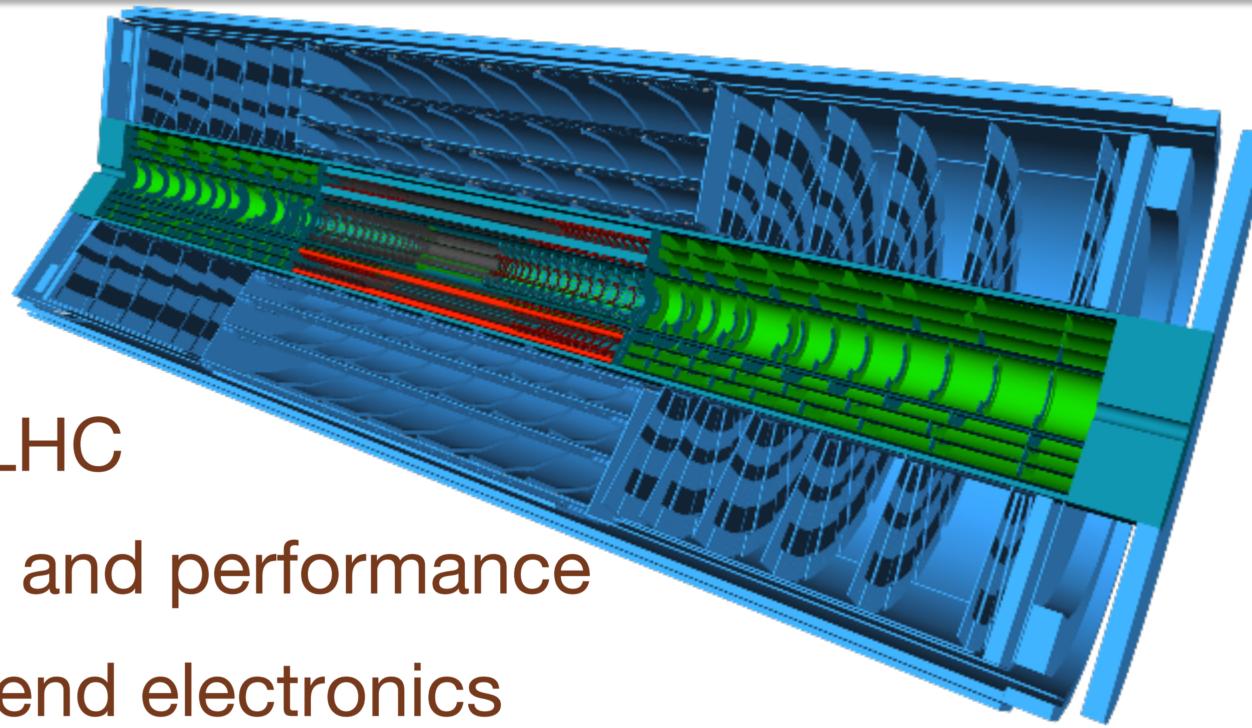
for the ATLAS Collaboration

PIXEL 2018

International Workshop on Semiconductor Pixel Detectors for Particles and Images

Academia Sinica, Taipei, 10-14 December 2018

Outline

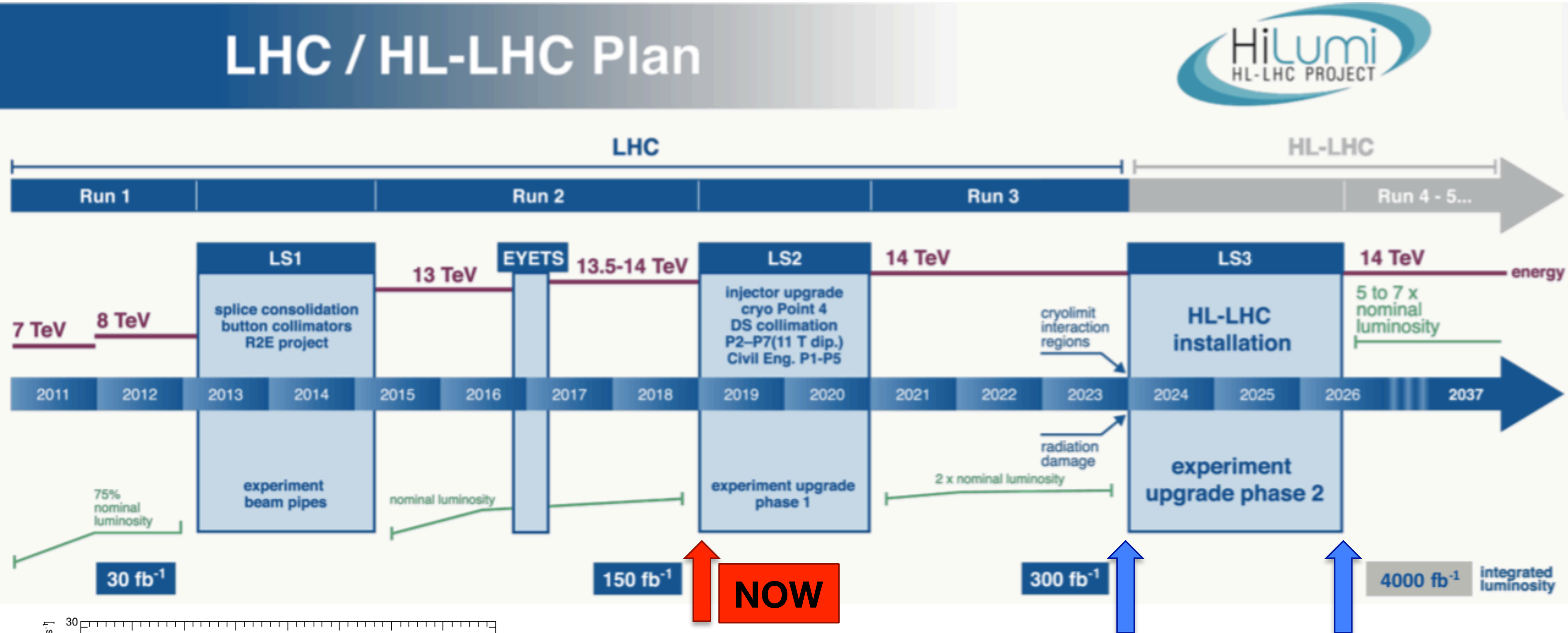


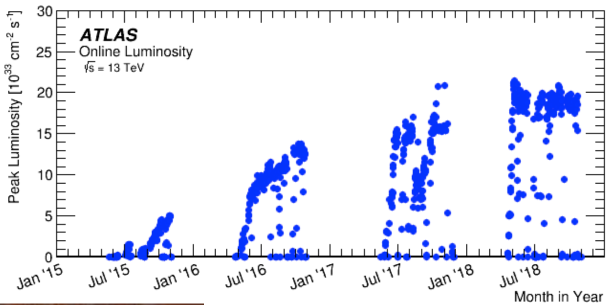
- The case for the ATLAS inner detector upgrade for the HL-LHC
- Pixel detector layout and performance
- Detectors and front-end electronics
- Mechanics and services
- Overall system aspects (Trigger and DAQ) and Outlook

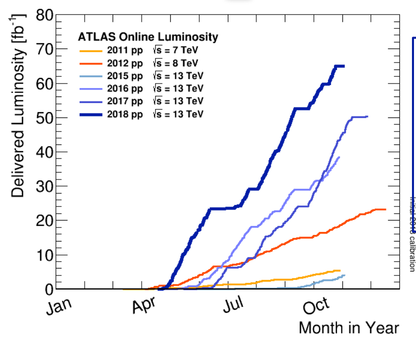
Technical Design Report
for the ATLAS Inner Tracker Pixel Detector
ATLAS-TDR-030 / CERN-LHCC-017-01

ITK REQUIREMENTS AND LAYOUT

The HL-LHC upgrade





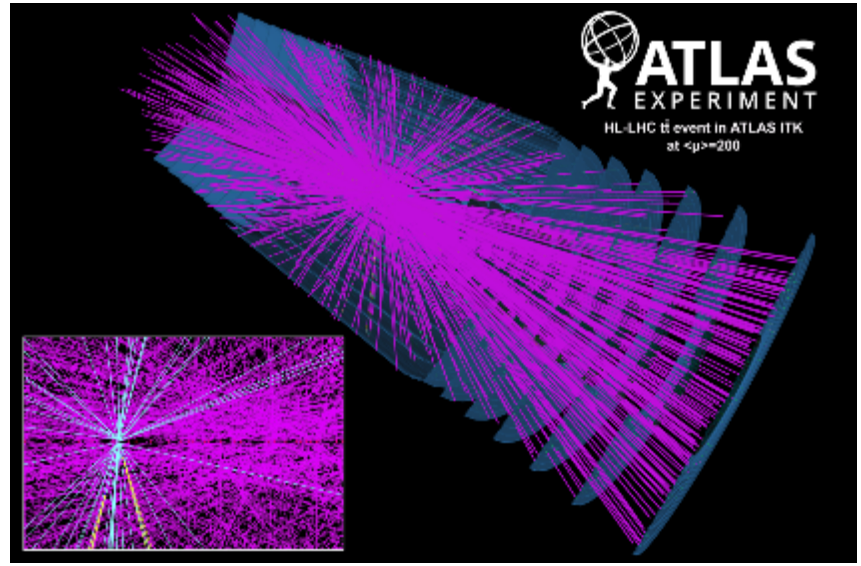


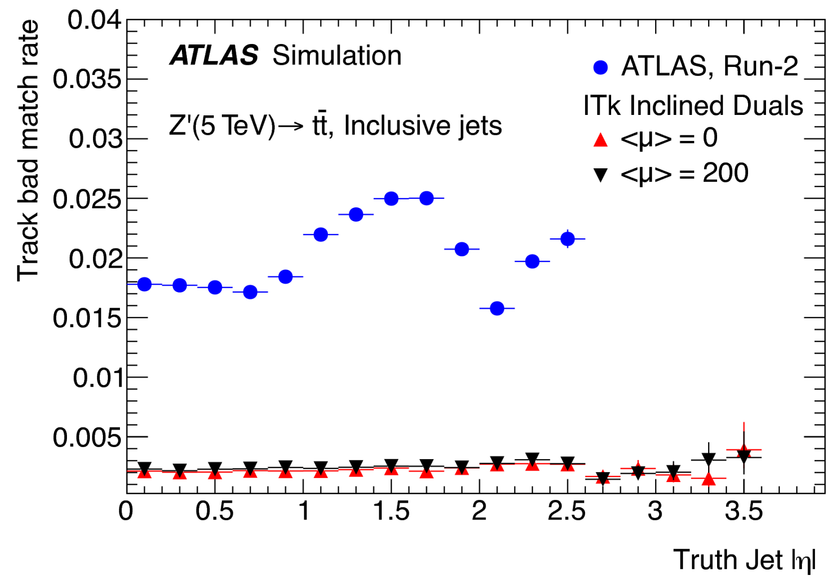
Current pixel detector
$L = 2 \times 10^{34}\ cm^{-2}s^{-1}$
$\int L = 300\ fb^{-1}$

ITk pixel detector
$L = 7 \times 10^{34}\ cm^{-2}s^{-1}$
$\int L = 4000\ fb^{-1}$

HL-LHC Physics Goals

- Rich physics program including:
  - Vector Boson Scattering
    - and other precision SM measurements
  - Higgs pair production
    - and precision Higgs boson properties
  - Beyond Standard Model searches
- Many reconstruction challenges:
  - High multiplicity events, highly boosted jets:
    - improve granularity and resolution
  - Rare events
    - improve in coverage and reconstruction efficiency





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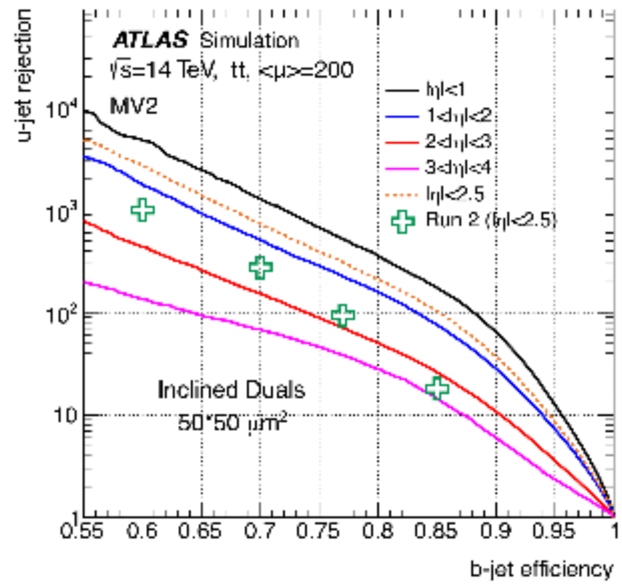
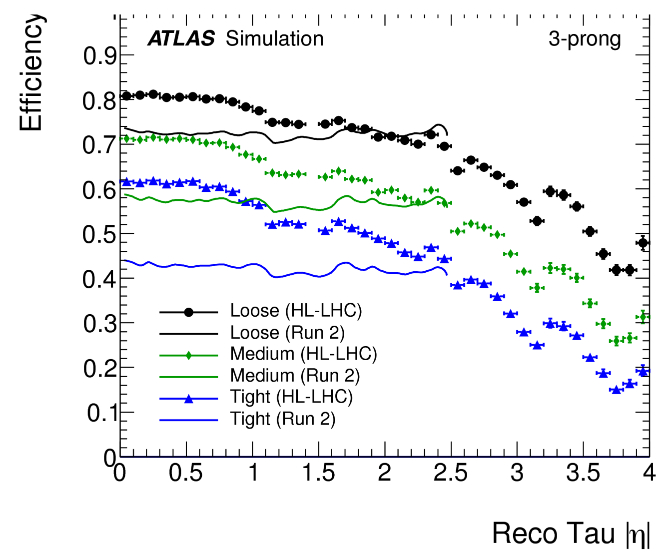




ITk requirements

Completely new inner detector

– full silicon tracker (TRT will have 100% occupancy)

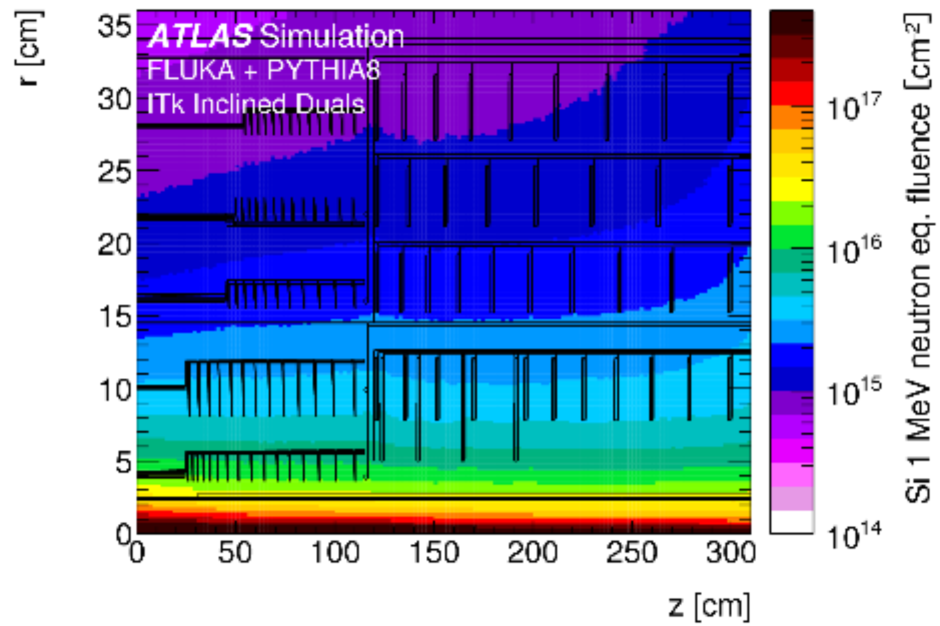
- Keep occupancy at few ‰ level
  - Increase granularity by 8× for the pixel, (5× with respect to the insertable B-layer)
  - expand pixels to a larger radius
- Increase data rate capability

Average hits / readout chip / event at 200 pile-up

(Ring) Layer	Flat Barrel	Inclined Barrel	End-cap
0	223.0	136.7	80.9
1	26.6	27.8	37.7
2	19.3	20.1	21.0
3	12.9	12.7	13.3
4	9.9	9.1	9.3

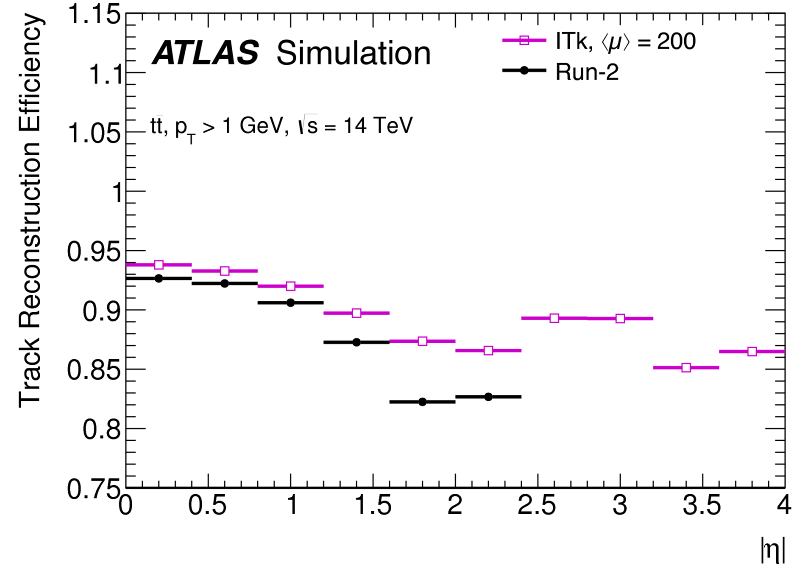
from 24 Mhits $mm^{-2}s^{-1}$ to 0.1 Mhits $mm^{-2}s^{-1}$

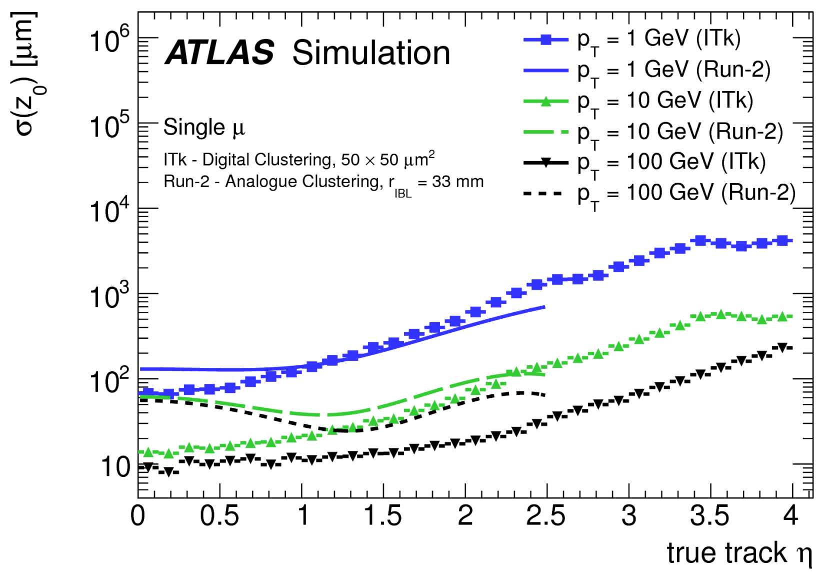
- Radiation hardness for 4000 fb^{-1}:
  - Non ionizing energy loss (NIEL) up to Φ_{eq} = (2.5-3)×10^{16} n/cm^2.
  - Total ionization dose (TID) up to 20 MGy

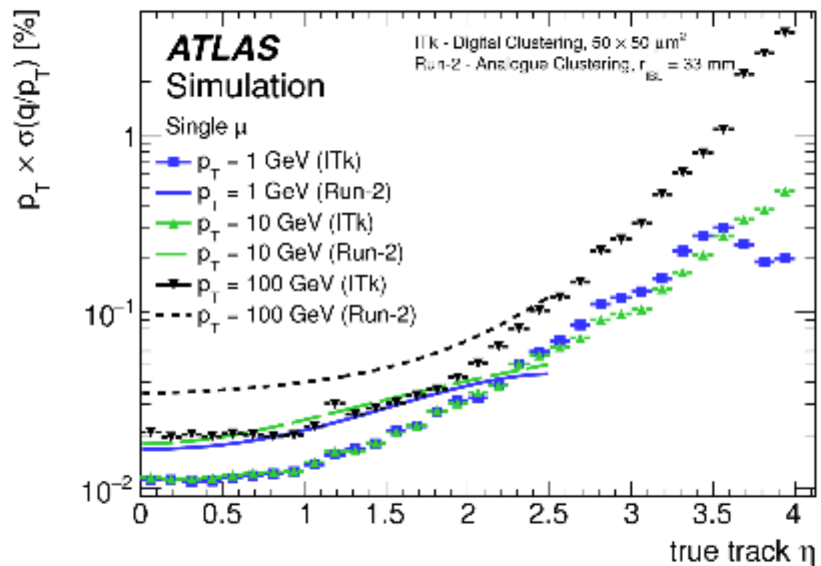


ITk requirements

- Improve resolution and robustness compared to the present detector:
  - track reconstruction efficiency >99% for muons, >85% for electrons and pions
  - fake rate < 10^{-5}
  - robustness against loss of up to 15% of channels



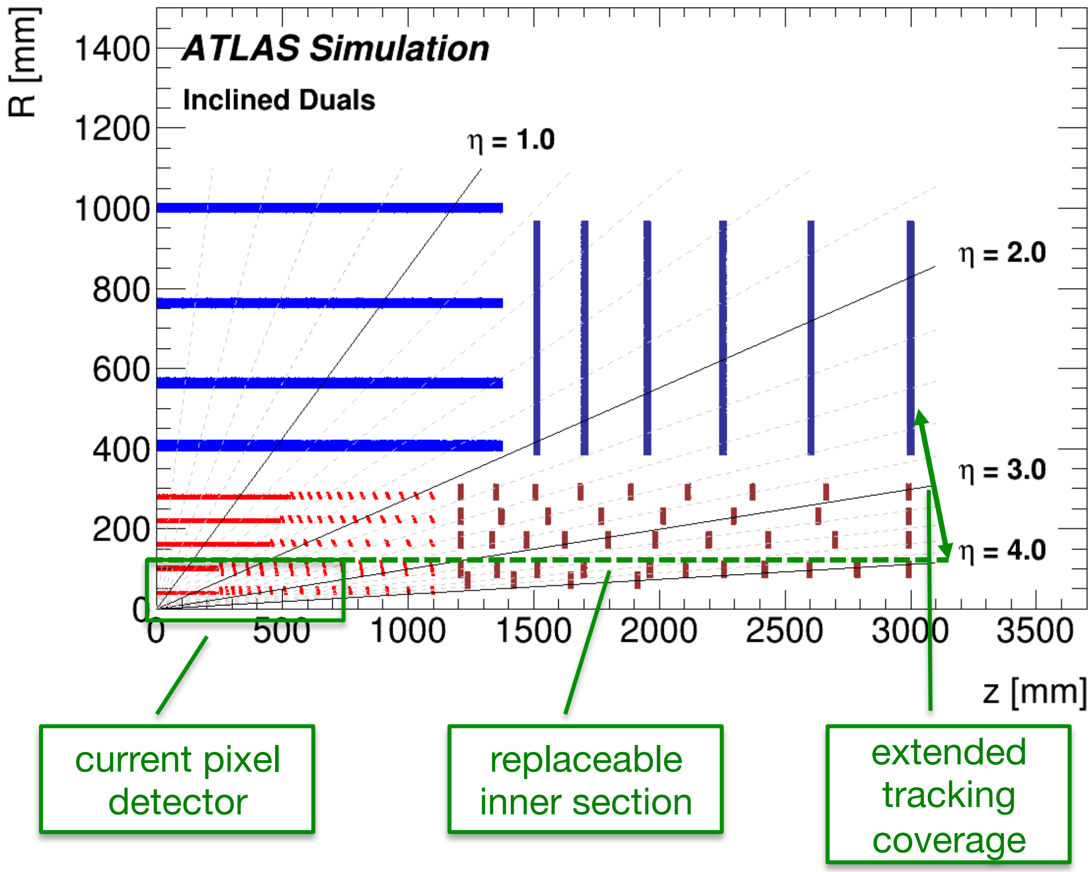




ITk layout

- Strips at outer radii, pixels near to the interaction region
- Cover with at least 9 measurements tracks up to $|\eta|=4$

- Pixel detector:
  - 12.7 m^2, 5×10^9 channels
  - 50×50 μm^2 or 25×100 μm^2
  - **inclined modules** and **individually placed disks**
    - minimize material and maximize resolution while keeping full coverage
  - inner section replaceable after 2000 fb^{-1}

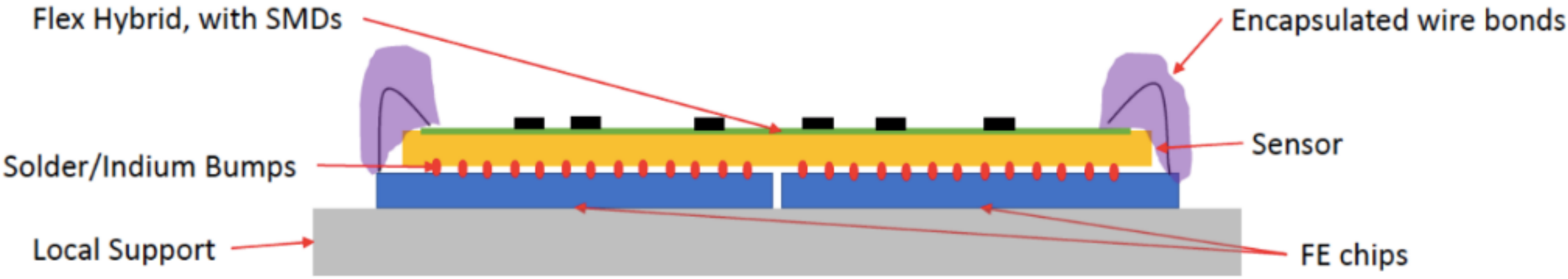


The active components

SENSORS AND FRONT-END

Hybrid module structure

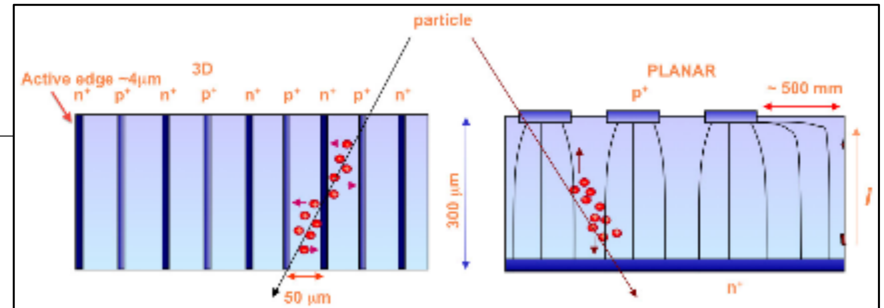
- Baseline design mainly consists of ~4×4 cm^2 "quad hybrid" modules:
  - one sensor segmented into either 50×50 μm^2 or 25×100 μm^2 pixels
  - read out by four FE chips, each with 384×400 channels

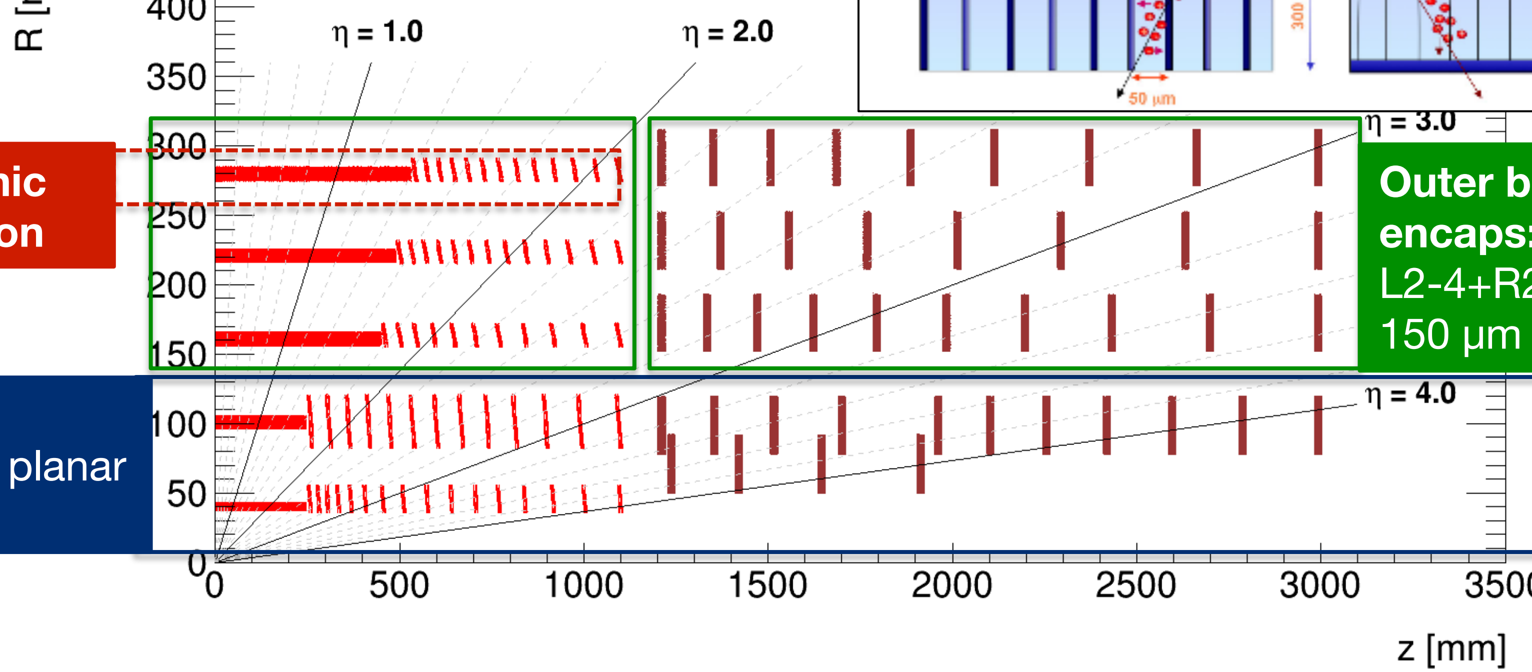


A lot of experience from current detectors, but needs to scale up a factor 10 in total production

Sensor technologies

- One front-end for the whole detector
  - RD53 collaboration: joint ATLAS and CMS effort on common 65 nm design
  - Requirements given by the innermost layers
- Sensor technology baseline optimized according to radiation hardness, cost and foundries production capability





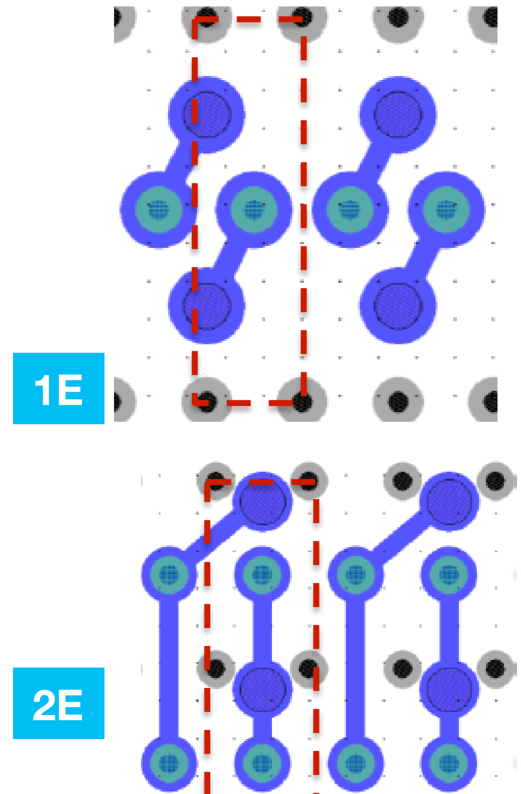
L4 monolithic CMOS option

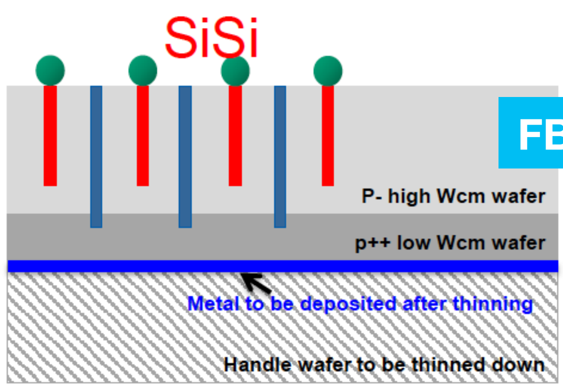
Outer barrel and encaps:
L2-4+R2-4
150 μm planar

Inner section:
L1+R1 100 μm planar
L0+R0 3D

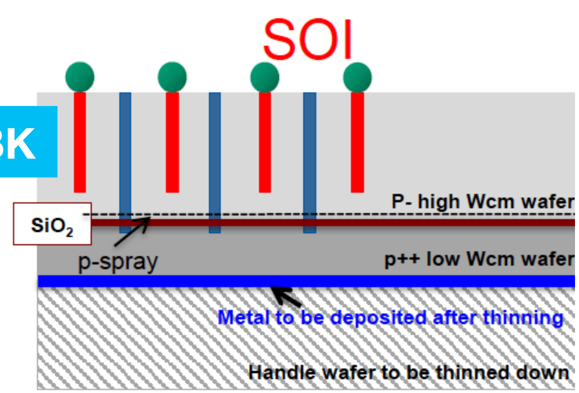
3D Sensors

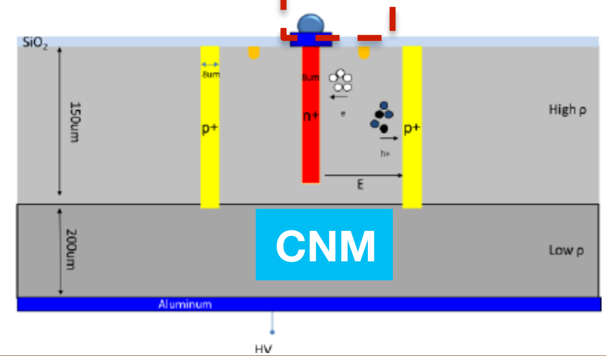
- Innermost layer: 1.3×10^{16} n_{eq}/cm^2 for 2000 fb^{-1}
  - 150 µm thickness + 100 µm support wafer
  - Single-chip dies ~2×2 cm^2
  - Sensor produced at FBK, CNM and Sintef
    - 50×50 μm^2 assessed
    - 25×100 μm^2 to be verified with RD53A assembly: radiation hardness of 1 Electrode design vs. yield for 2 Electrodes design





FBK

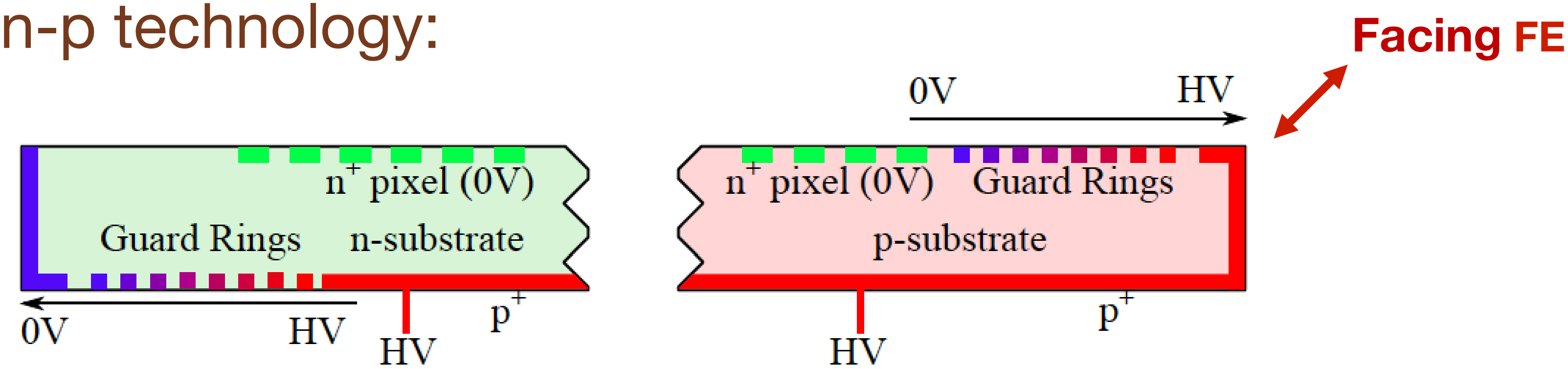




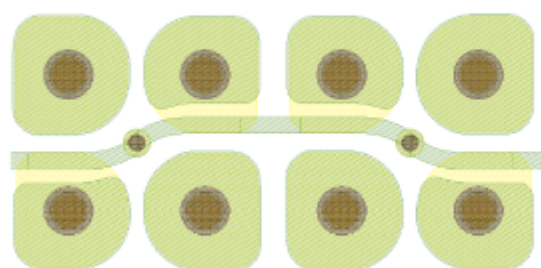
CNM

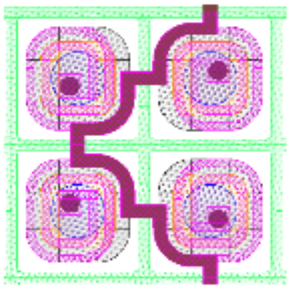
Planar sensors

- Use n-in-p technology:

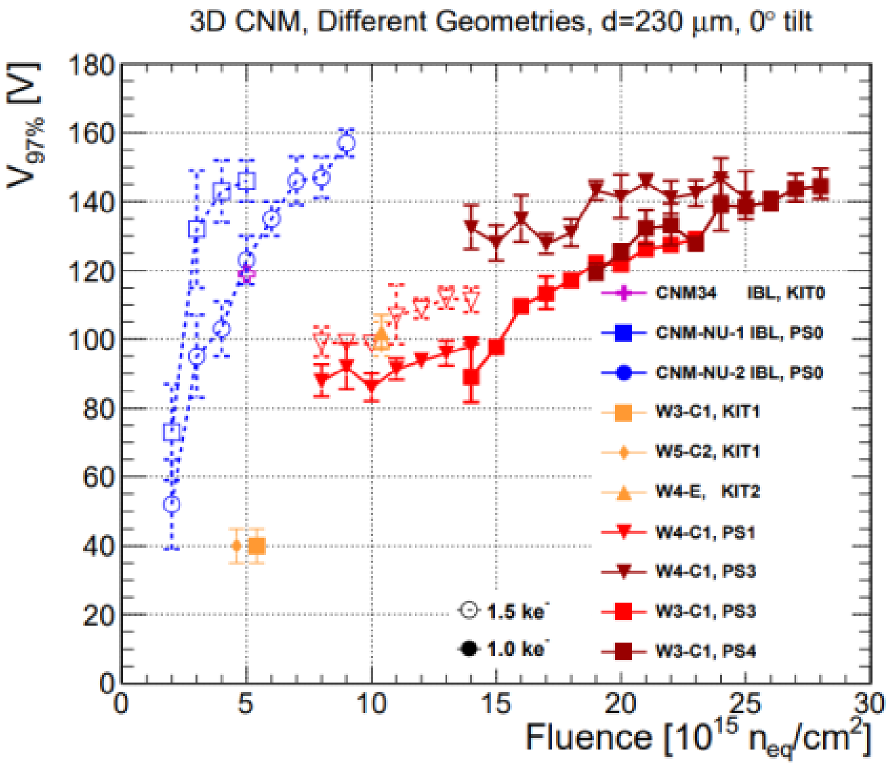


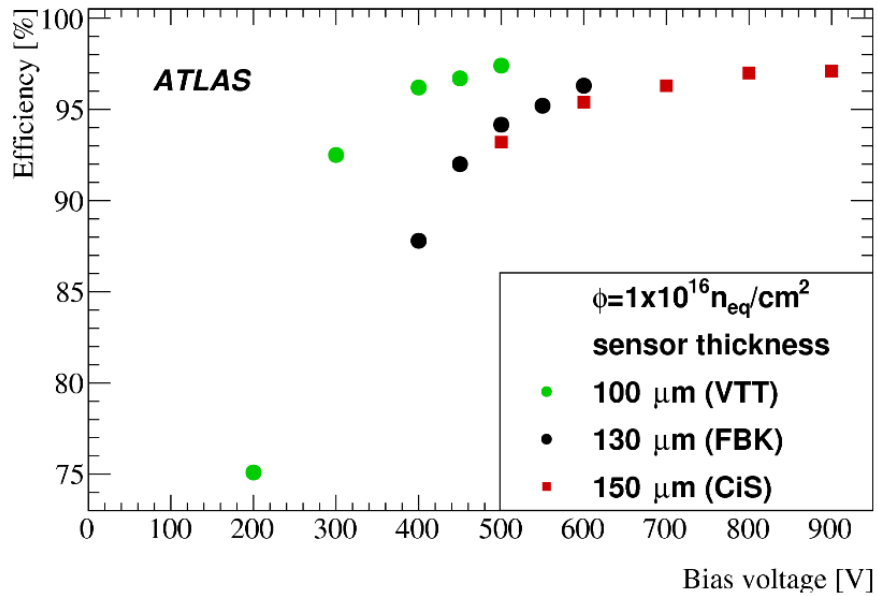
  - One side processing: reduced cost and easier handling
  - HV protection between sensor-edge and FE electronics:
    - BCB or Parylene under evaluation
- Thin sensors in inner section: 4.5×10^{15} n_{eq}/cm^2 for 2000 fb^{-1}
  - Hit efficiency saturation at lower bias voltage: smaller leakage current and power consumption
  - Critical point is efficiency loss due to bias structures
  - Many vendors on the market: CiS, FBK, HPK, Lfoundry. Micron, VTT…



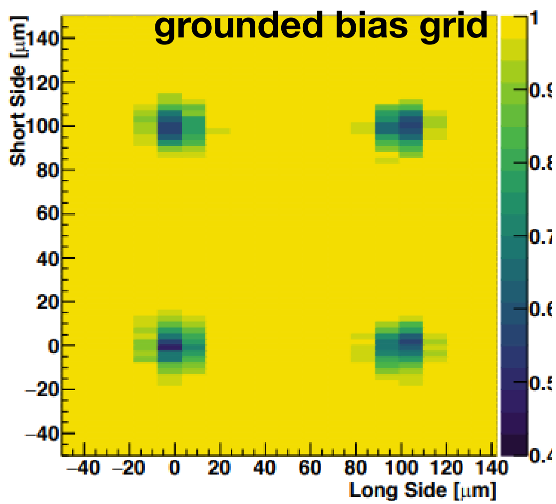


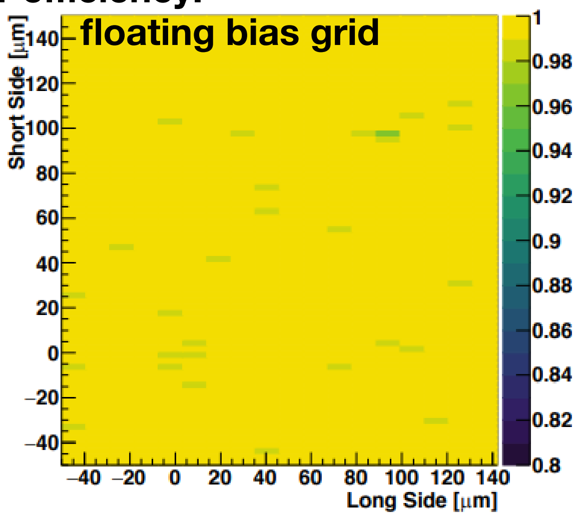
Sensor performance





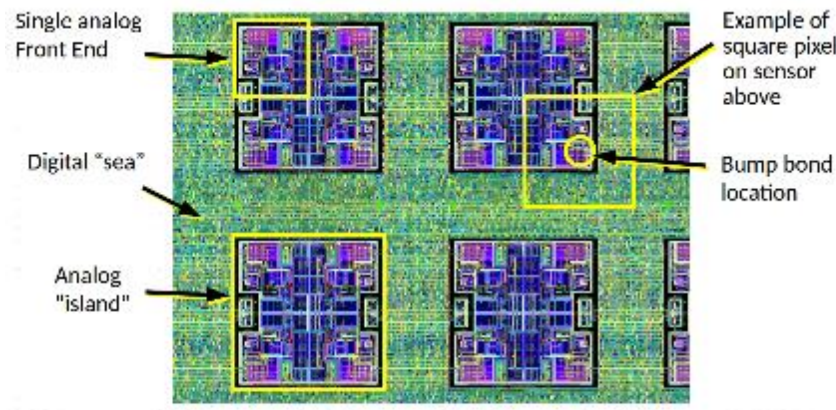
Planar sensor efficiency:

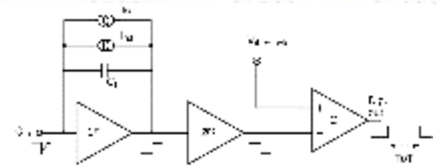


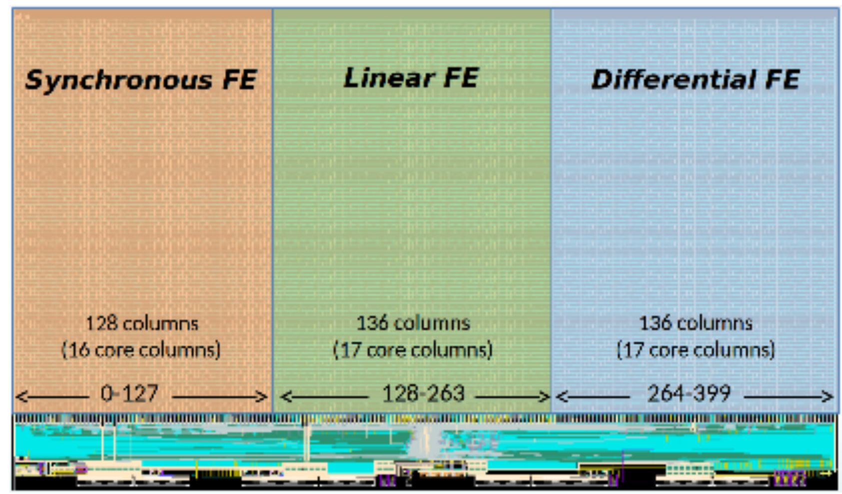


Front-end chip

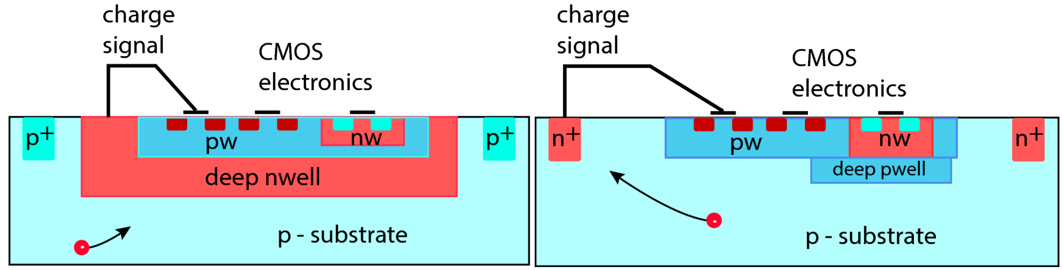
- RD53 Collaboration: joint ATLAS and CMS R&D
  - 65 nm TSMC technology
  - Final size ~2×2 cm^2 with ~160k pixels
  - ATLAS version mid 2019, CMS version few months later
  - Heavy use of modern design technologies to implement complex readout logic:
    - Managing ~223 hits/chip/bunch crossing
    - Local memory for 500 bunch crossing trigger latency
    - 4×1.28 Gb/s links with data compression
- RD53A FE demonstrator:
  - Full width / half depth chip
  - Being used for qualification of:
    - Sensor design
    - Powering scheme and DCS
    - Module assembly and handling



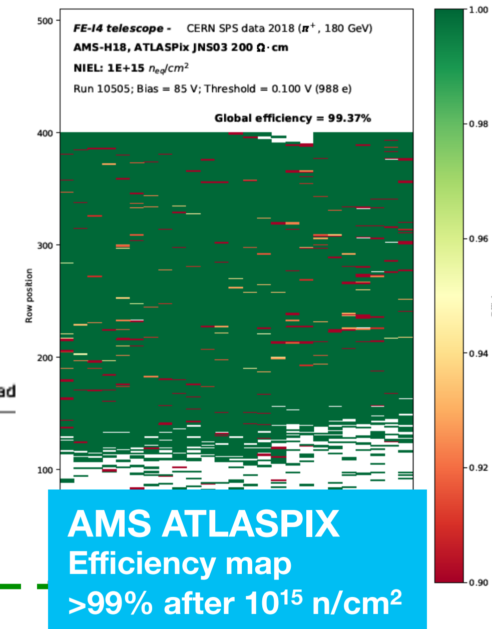


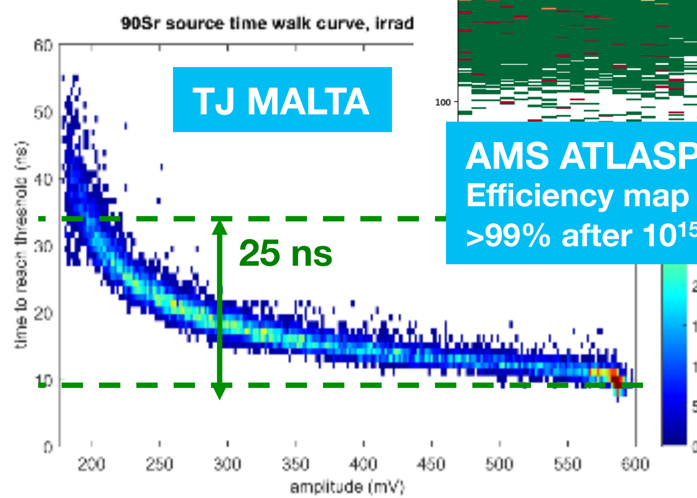


Monolithic CMOS option



- Depleted CMOS Detectors
  - Charge collection by drift provides radiation hardness and timing resolution similar to planar sensors
  - Large electrode designs (AMS/TSI, Lfoundry) have consistently shown high efficiency after irradiation
  - Small electrode design (TowerJazz) very promising in term of noise, time resolution and power consumption
- Technically feasible for outermost layer
  - "relaxed" requirements:
    - NIEL: 1.5×10^{15} n_{eq}/cm^2 ,
    - TID: 0.8 MGy
    - ~10 hits/chip/bunch crossing
  - Large saving factor:
    - L4 is 3 m^2, 30% of all thick sensor productio



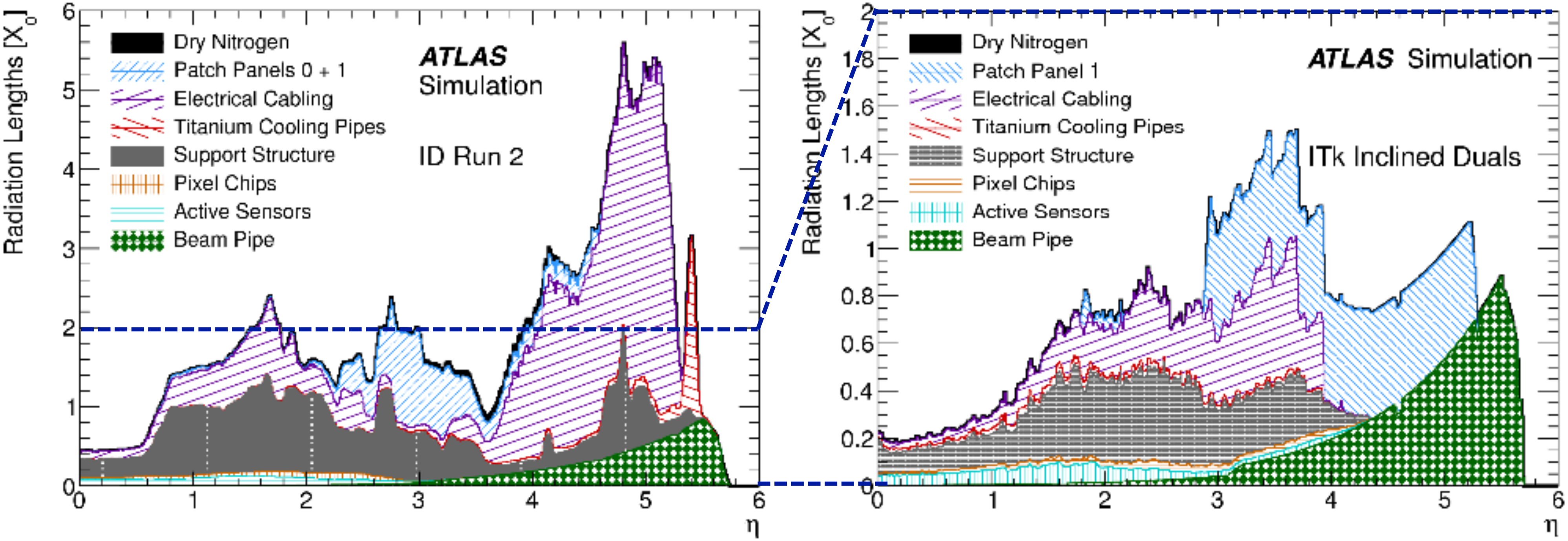


The path to performance

MECHANICS AND SERVICES

Material budget

- Reduction of material is the key to:
  - Resolution for low momentum particles
  - Tracking efficiency (dominated by interaction with the detector)

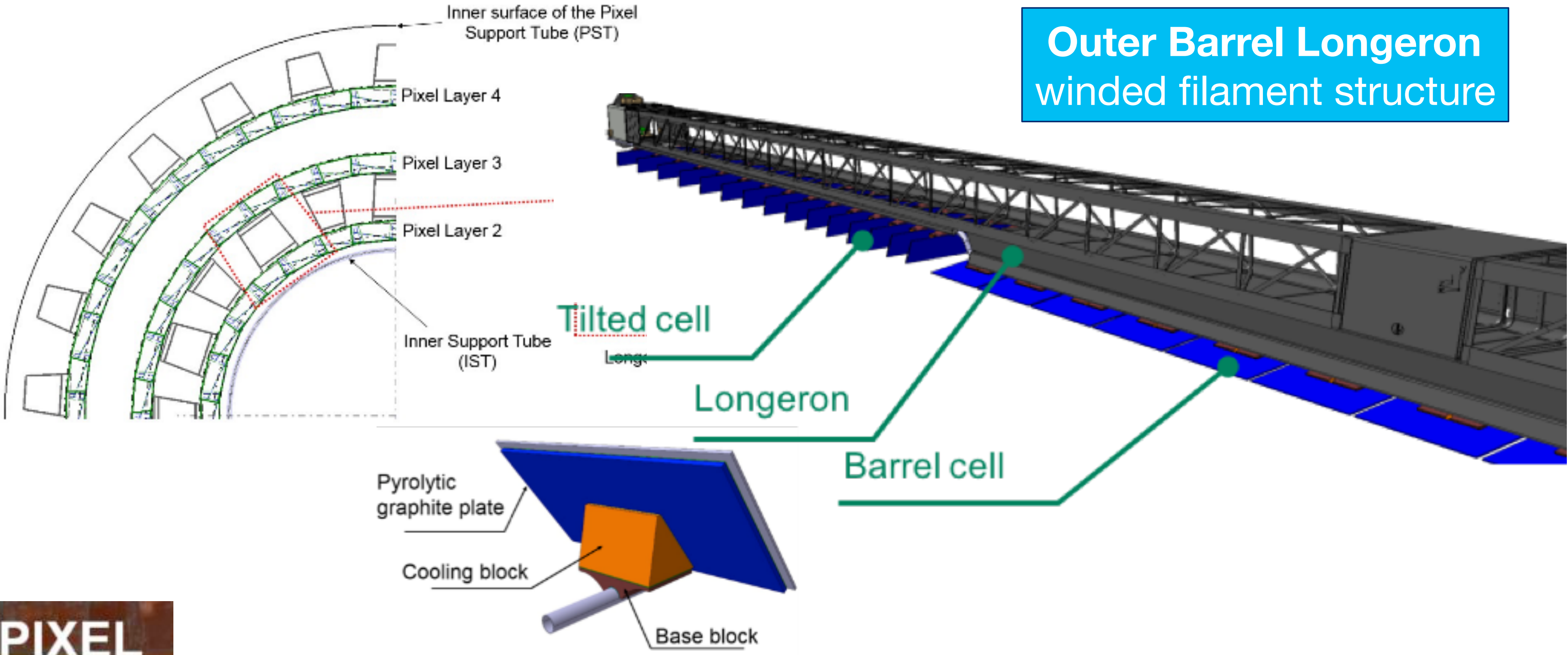


Improved design of services!

Local supports

- Lightweight carbon-carbon structures
- $C0_2$ evaporative cooling with Ti pipes

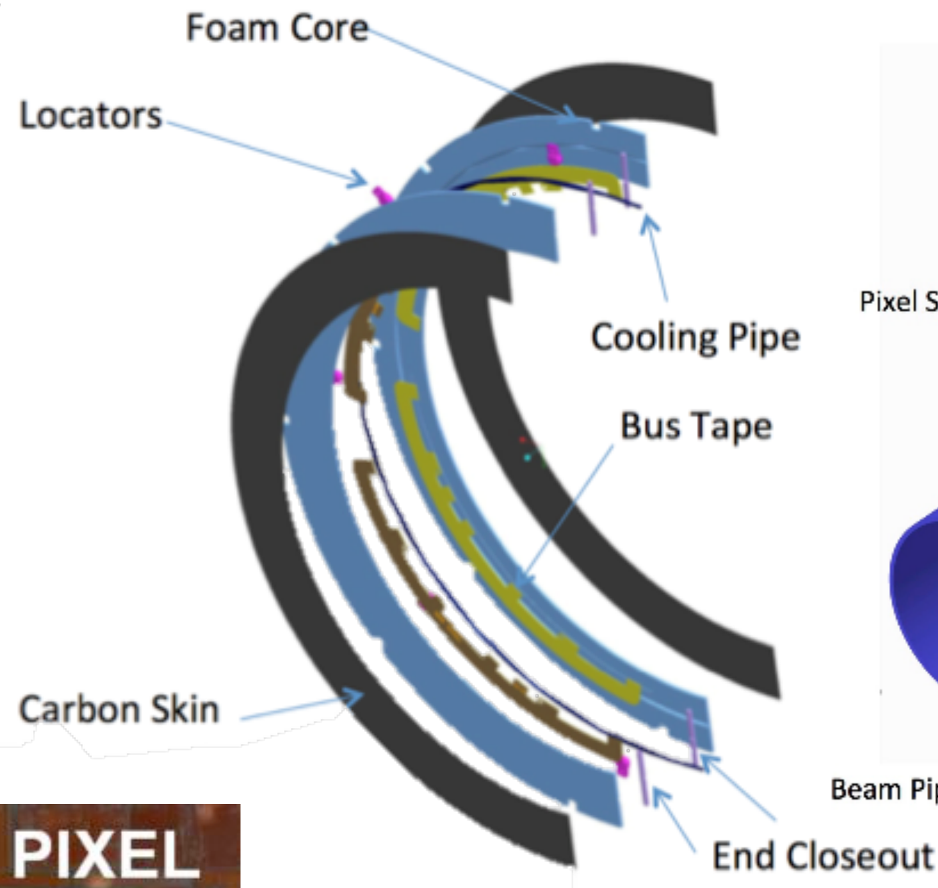
Outer Barrel Longeron
winded filament structure

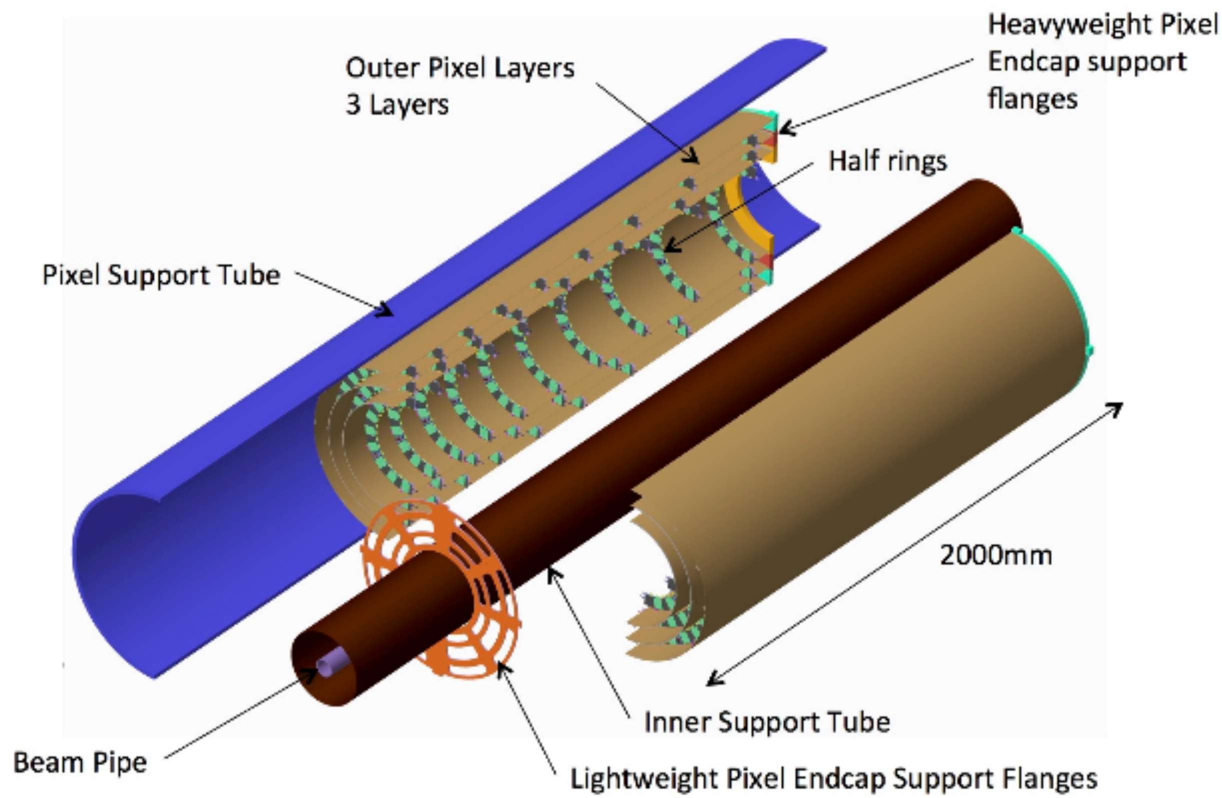


Local supports

- Lightweight carbon-carbon structures
- $C0_2$ evaporative cooling with Ti pipes

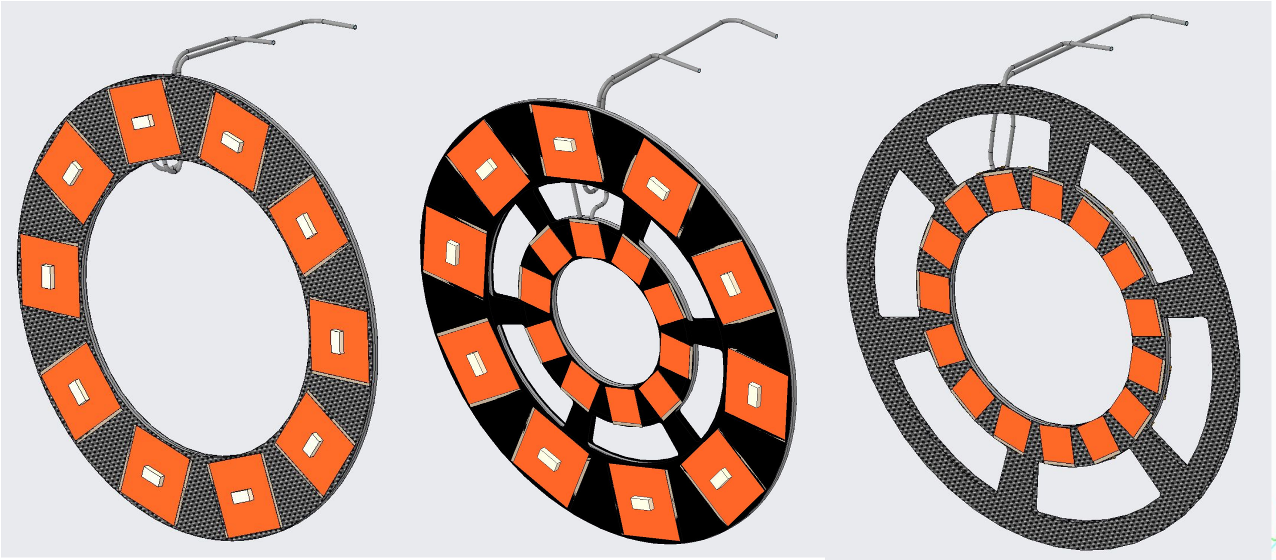
Outer Endcap
Halfrings

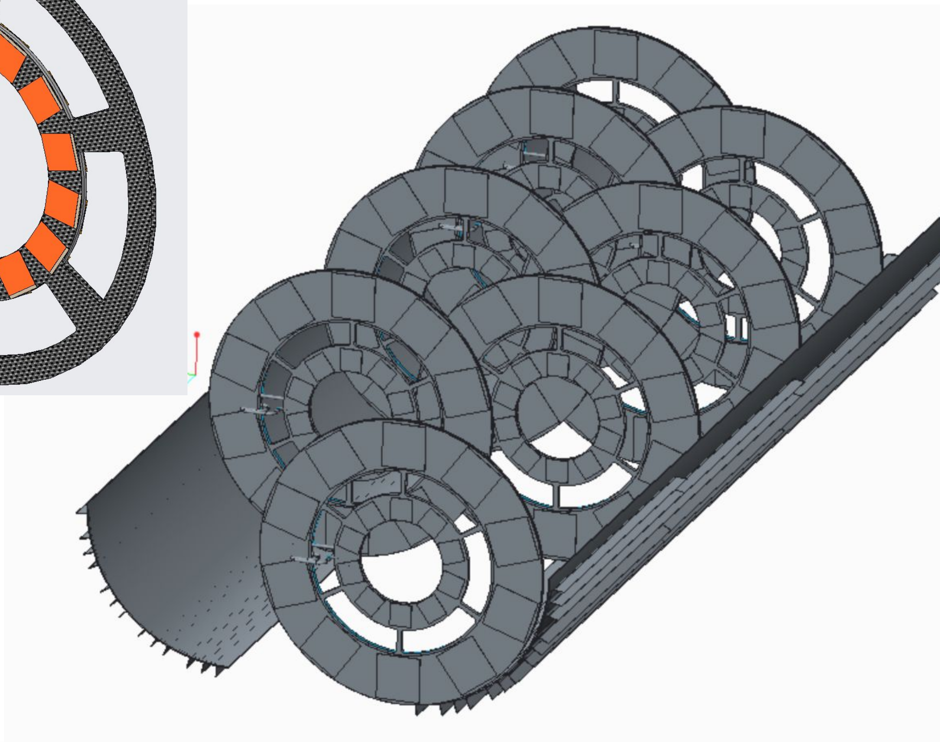




Local supports

- Lightweight carbon-carbon structures
- CO_2 evaporative cooling with Ti pipes

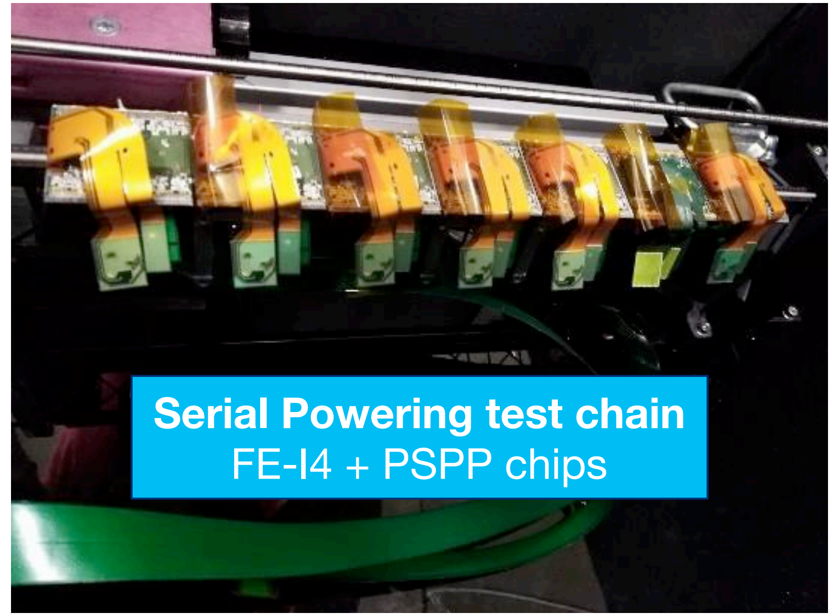


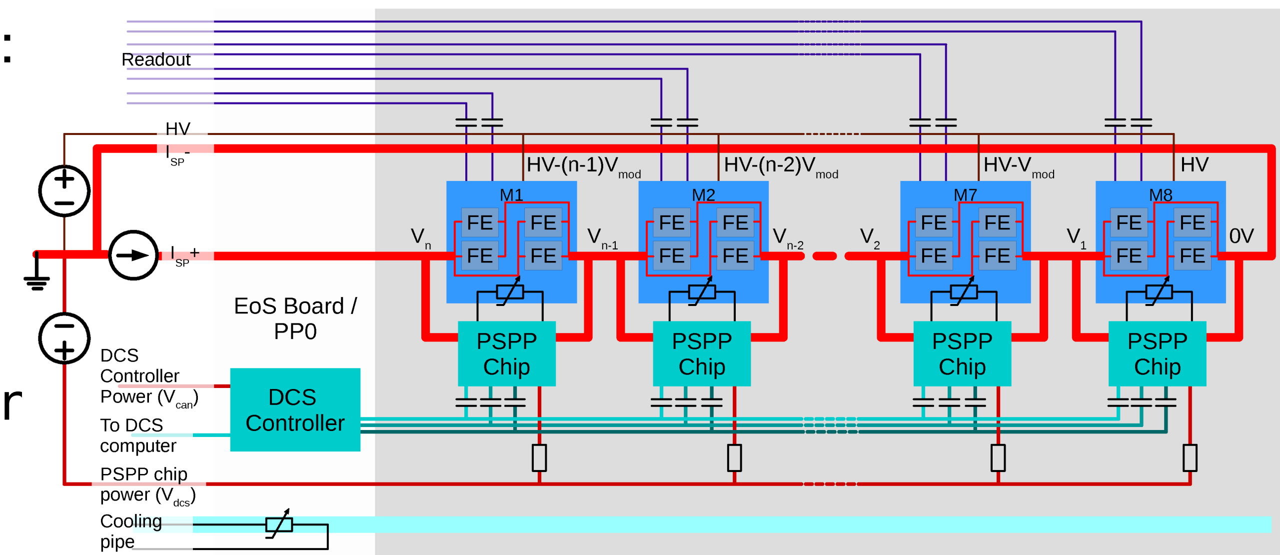


Inner Endcap
Single or coupled disks

Serial powering

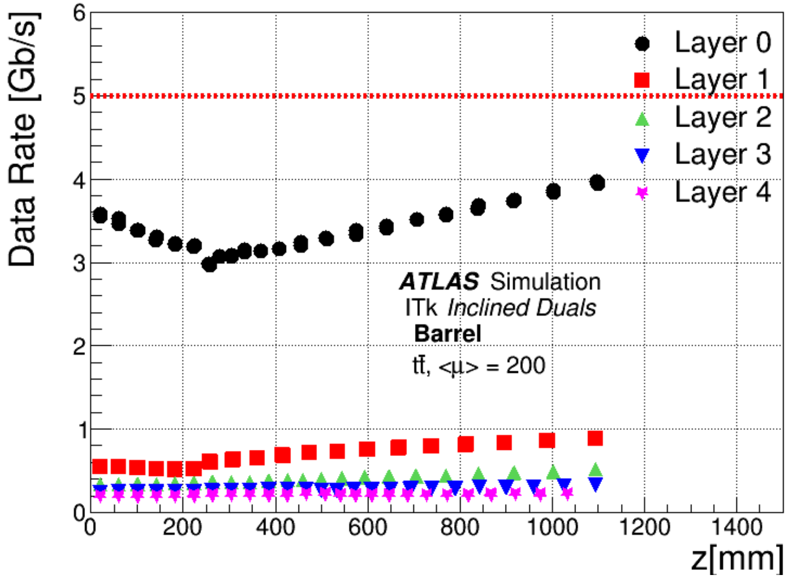
- Strong reduction in cable lines and material
- Up to 7A/8W on a quad-module
- Up to 14 modules in a single serial power chain
  - Need to provide a safety mechanism in case of module failure
  - Detector Control System:
    - Hardwired safety interlock
    - PSPP Chip + DCS Controller
    - Diagnostic informatior from FE

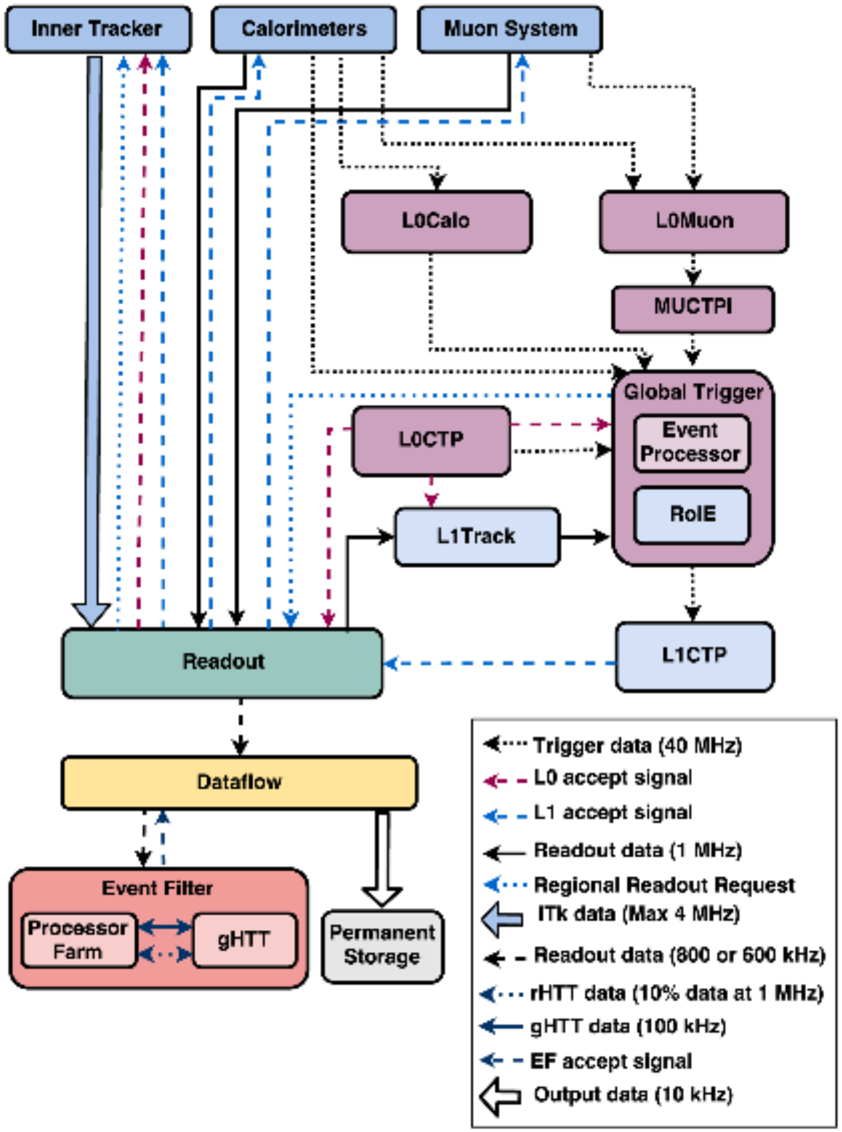




Trigger scheme

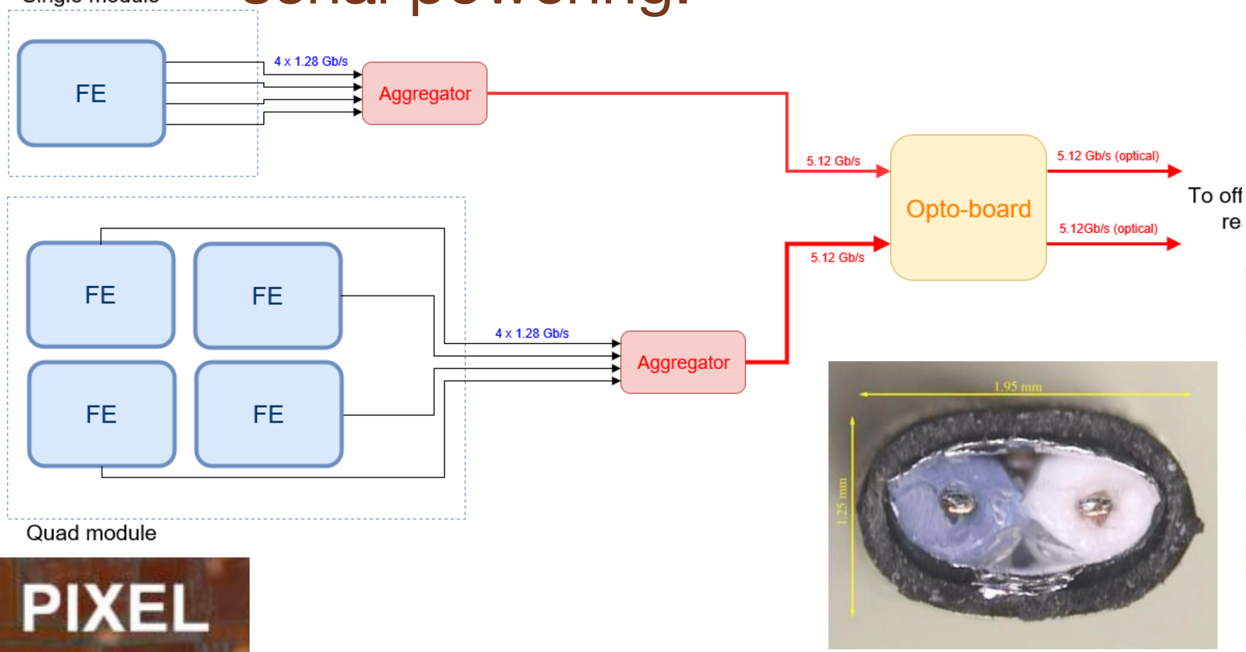
- Considering two trigger schemes:
  - 1 MHz 1-level trigger
    - 12.5 μs trigger latency
    - Fast track reconstruction for HLT
  - 4 MHz 2-level trigger
    - 25 μs readout latency
    - L1 track trigger (outer layers+strips)

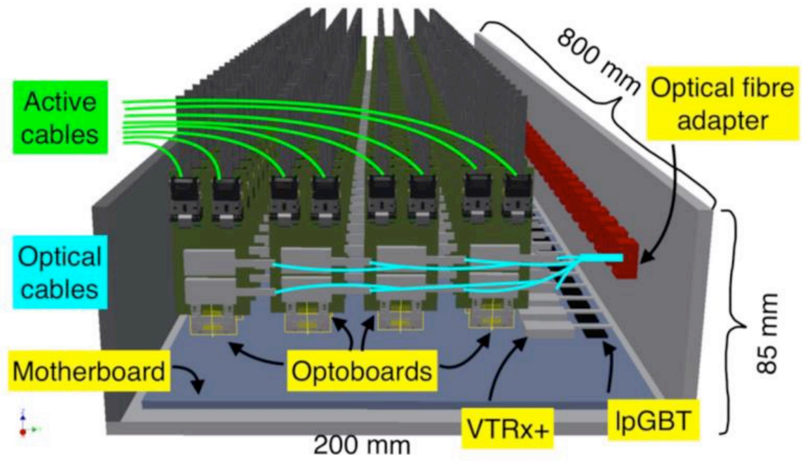




Data transmission

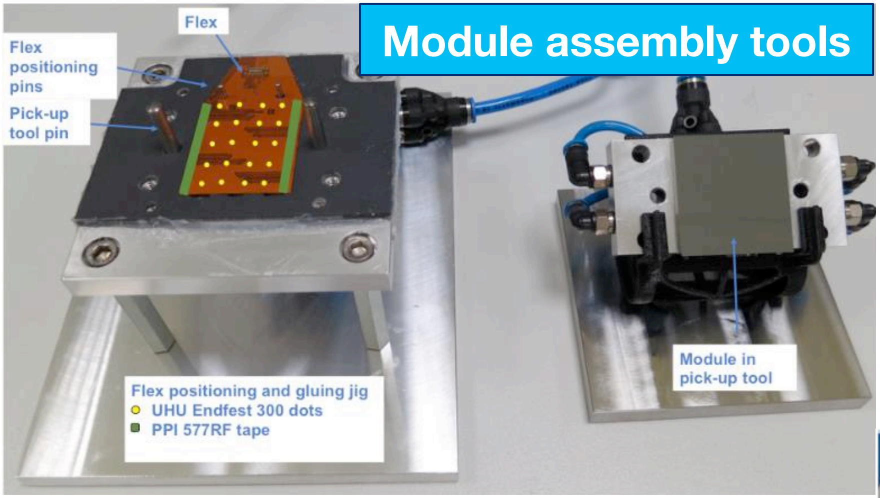
- Output links at 5.12 Gb/s, with Aurora 64/62 encoding
- Concentrate the 1.28 Gb/s FE outputs near to modules
  - Position-dependent modularity
- Thin cables (twin-ax) till optoboards
- AC coupling: each FE is at different ground level due to serial powering.

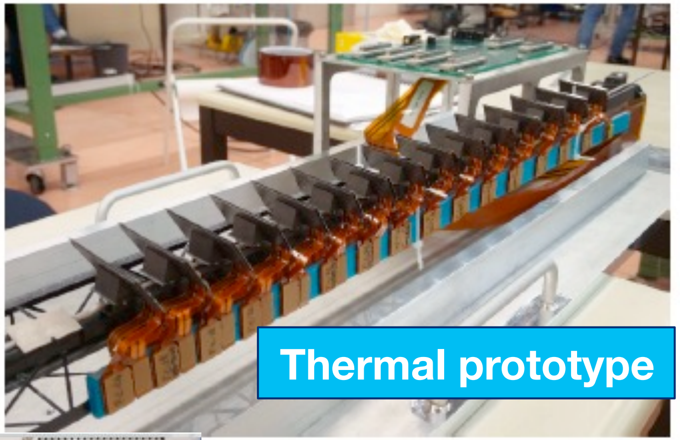


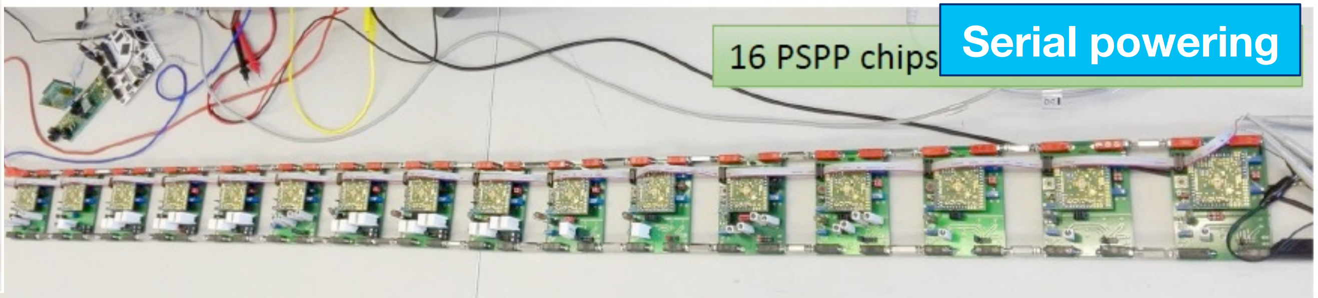


CONCLUSIONS

Prototyping



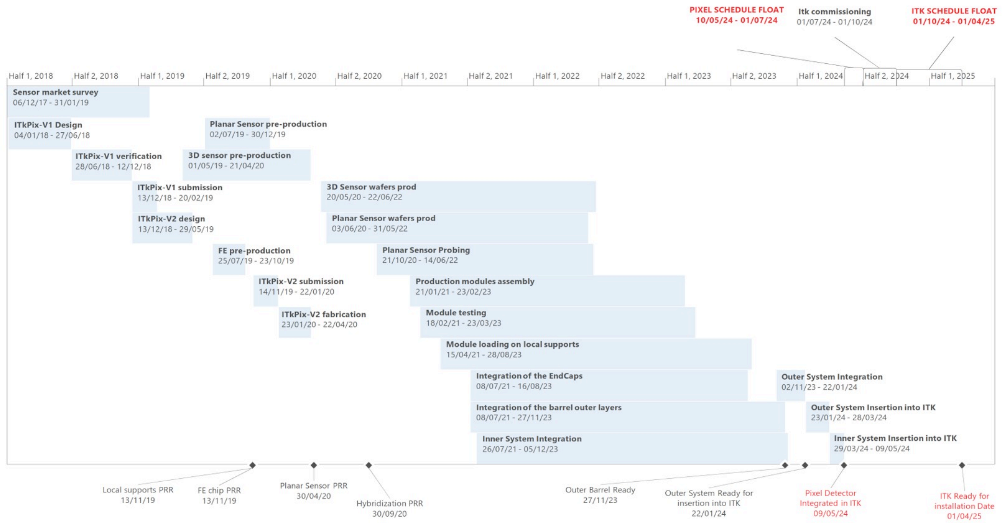


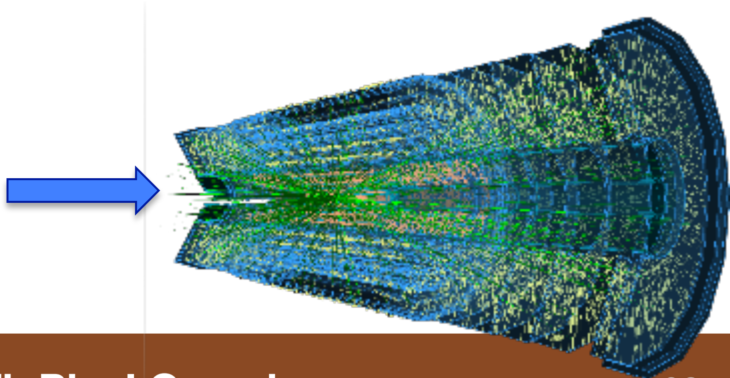


Intense activity to prepare for the detector construction

Conclusions

- The ITk Pixel Detector project is a non trivial challenge improve the high–performance devices already operating at the LHC:
  - 7× instantaneous luminosity
  - 13× integrated luminosity
  - 99.93% of solid angle coverage
- Innovation is required not only on the detector side, but also on services.
- About one year after the TDR the project is running at full speed to be ready for HL-LHC first collisions!





ATLAS ITk Talks and Posters

Hybrid Pixel

- **Modeling Radiation Damage to Pixel Sensors in the ATLAS Detector**
  - Marco Bomben, 11th December 16:20
- **Performance of FBK/INFN/LPNHE thin active edge n-on-p pixel detectors for the upgrade of the ATLAS Inner Tracker**
  - Giovanni Calderini, 11th December 11:10
- **Characterization of RD53A compatible n-in-p planar pixel sensors**
  - Anna Macchiolo, 11th December 11:35
- **Study of efficiency and noise of fine pitch planar pixel detector for ATLAS ITk upgrade**
  - Koji Nakamura, 11th December 12:25
- First CMS results on 3D pixel sensors interconnected to RD53A readout chip after high energy proton irradiation
  - Marco Meschini, 10th December Poster session

- **Radiation-induced effects on data integrity and -link stability of RD53A**
  - Marco Vogt, 11th December 17:35

ATLAS ITk Talks and Posters

Modules

- **Module Development for the Phase-2 ATLAS ITk Pixel Upgrade**
  - Dai Kobayashi, 10th December Poster session
- **Results of larger structures prototyping for the Phase-II upgrade of the pixel detector of the ATLAS experiment**
  - Susanne Kuehn, 13th December 17:35
- **A 5.12 Gbps serial data receiver for active cable for ATLAS Inner Tracker Pixel Detector readout upgrade**
  - Le Xiao, 10th December Poster Session

ATLAS ITk Talks and Posters

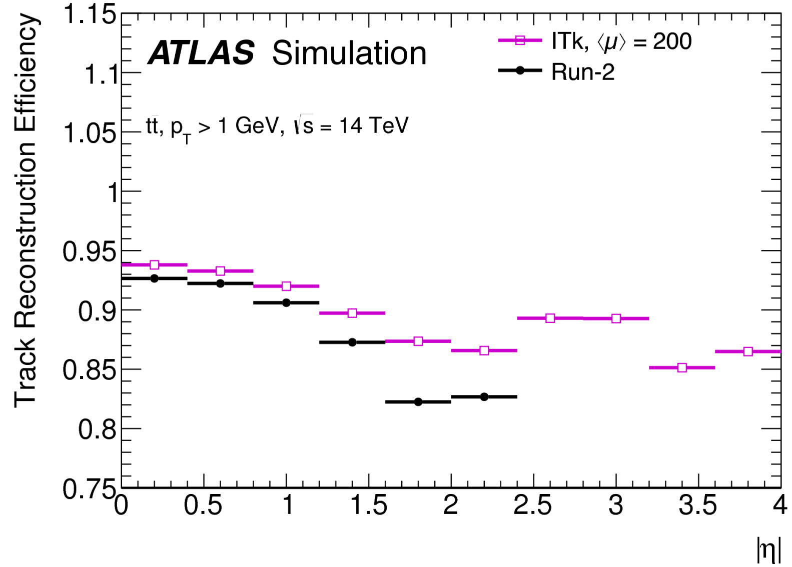
Depleted CMOS

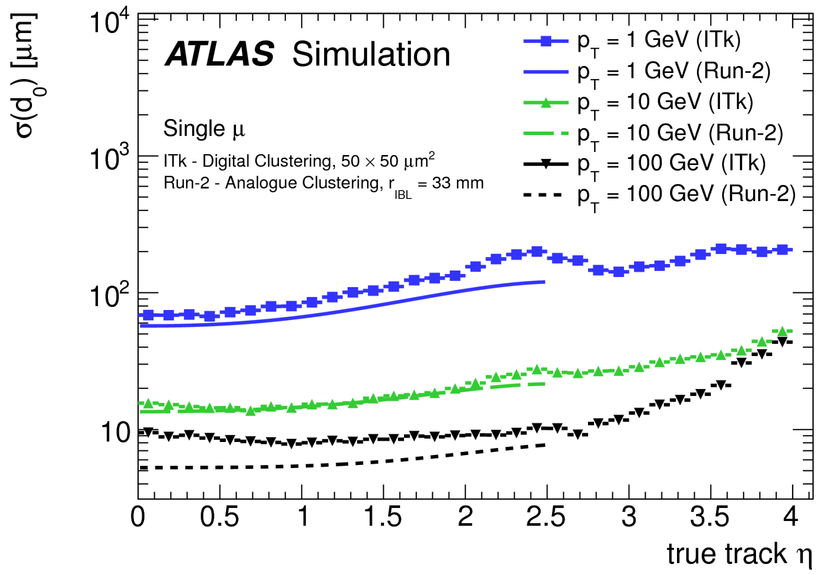
- **R&D status of the Monopix chips: Depleted monolithic active pixel sensors with a column-drain read-out architecture for the ATLAS Inner Tracker upgrade**
  - Ivan Dario Caicedo Sierra, 13th December 11:10
- **MALTA: an asynchronous readout CMOS monolithic pixel detector for the ATLAS High-Luminosity upgrade**
  - Roberto Cardella, 11th December 12:00
- **Simulations of CMOS sensors with a small collection electrode improved for a faster charge-collection and increased radiation tolerance**
  - Ruth Magdalena Munker, 10th December 12:25
- **Performance of the ATLASPix1 pixel sensor prototype in ams aH18 CMOS technology for the ATLAS ITk upgrade**
  - Moritz Kiehn, 13th December 12:00
- **Electrical characterization of AMS aH18 HV-CMOS after neutrons and protons irradiations**
  - D M S Sultan, 10th December 12:00
- **Developments towards a Serial Powering scheme in a monolithic CMOS technology for the ATLAS pixel upgrade**
  - Siddharth Bhat, 10th December Poster session

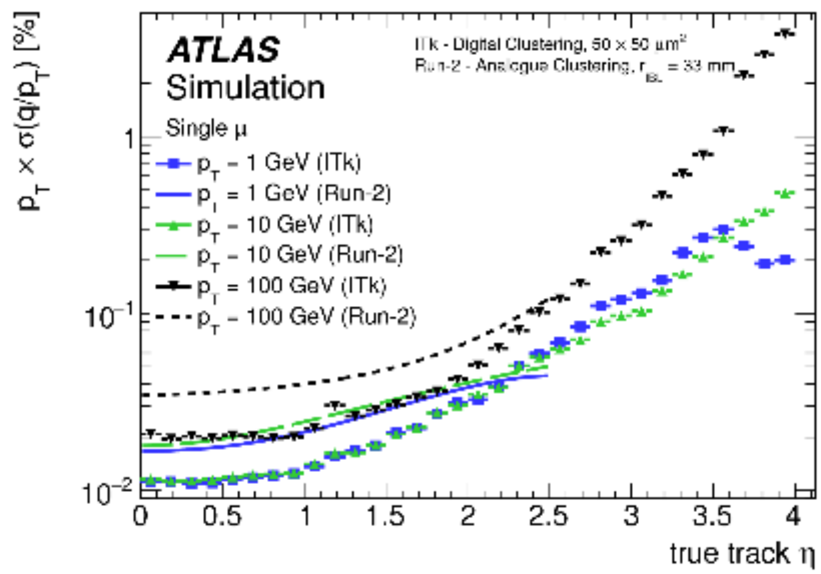
ADDITIONAL MATERIAL

ITk requirements

- Improve resolution and robustness compared to the present detector:
  - track reconstruction efficiency >99% for muons, >85% for electrons and pions
  - fake rate < 10^{-5}
  - robustness against loss of up to 15% of channels







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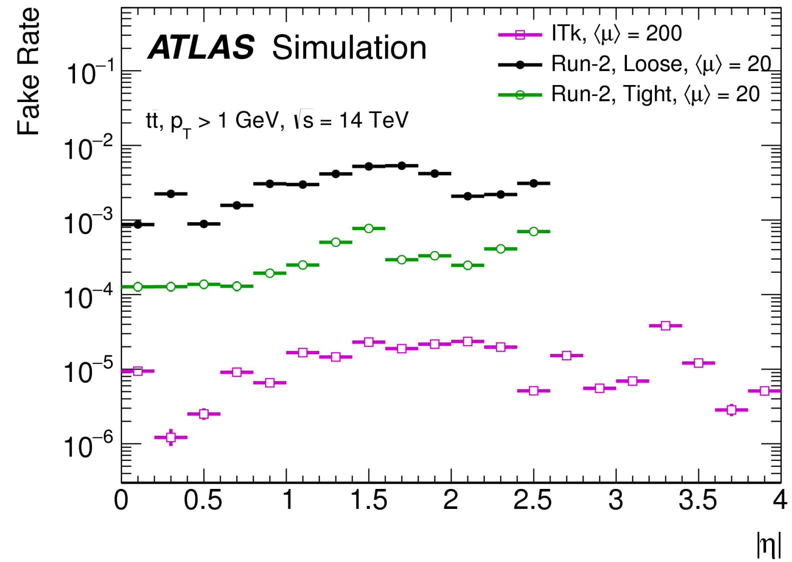
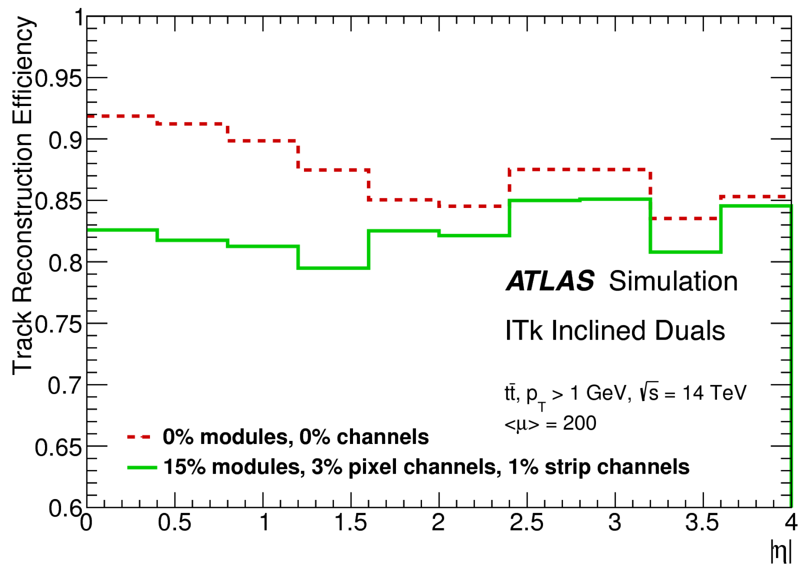
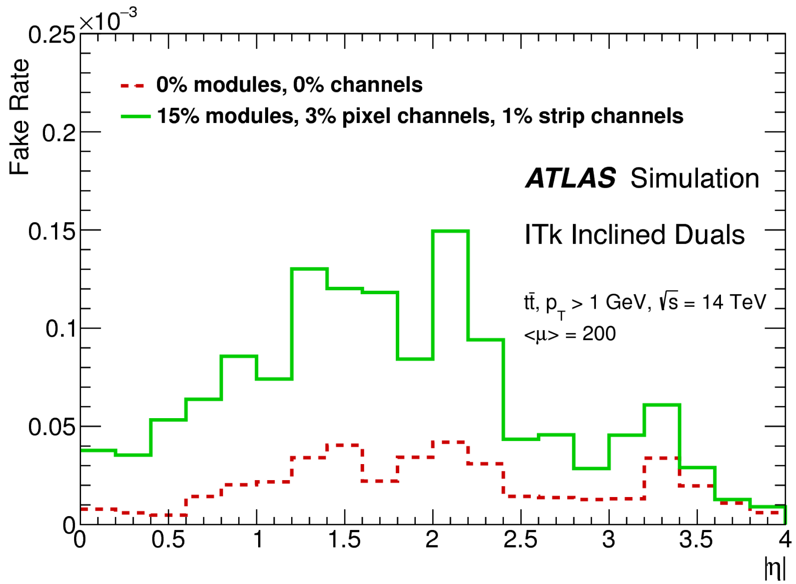
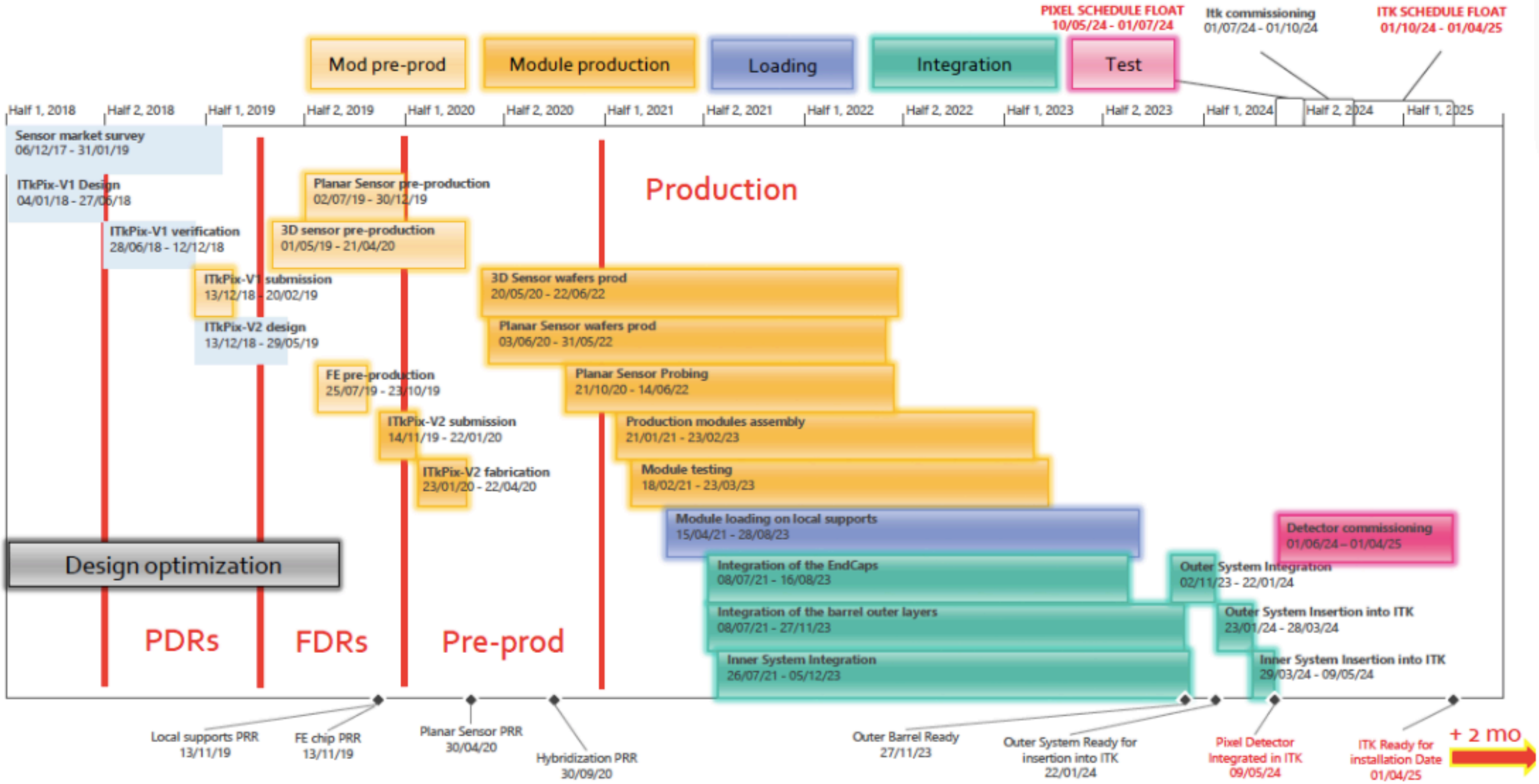






Schedule



PIXEL SCHEDULE FLOAT
10/05/24 - 01/07/24
Itk commissioning
01/07/24 - 01/10/24
ITK SCHEDULE FLOAT
01/10/24 - 01/04/25
Mod pre-prod
Module production
Loading
Integration
Test
Half 1, 2018
Half 2, 2018
Half 1, 2019
Half 2, 2019
Half 1, 2020
Half 2, 2020
Half 1, 2021
Half 2, 2021
Half 1, 2022
Half 2, 2022
Half 1, 2023
Half 2, 2023
Half 1, 2024
Half 2, 2024
Half 1, 2025
Sensor market survey
06/12/17 - 31/01/19
ITkPix-V1 Design
04/01/18 - 27/06/18
ITkPix-V1 verification
28/06/18 - 12/12/18
ITkPix-V1 submission
13/12/18 - 20/02/19
ITkPix-V2 design
13/12/18 - 29/05/19
Planar Sensor pre-production
02/07/19 - 30/12/19
3D sensor pre-production
01/05/19 - 21/04/20
FE pre-production
25/07/19 - 23/10/19
ITkPix-V2 submission
14/11/19 - 22/01/20
ITkPix-V2 fabrication
23/01/20 - 22/04/20
Production
3D Sensor wafers prod
20/05/20 - 22/06/22
Planar Sensor wafers prod
03/06/20 - 31/05/22
Planar Sensor Probing
21/10/20 - 14/06/22
Production modules assembly
21/01/21 - 23/02/23
Module testing
18/02/21 - 23/03/23
Module loading on local supports
15/04/21 - 28/08/23
Detector commissioning
01/06/24 – 01/04/25
Integration of the EndCaps
08/07/21 - 16/08/23
Outer System Integration
02/11/23 - 22/01/24
Integration of the barrel outer layers
08/07/21 - 27/11/23
Outer System Insertion into ITK
23/01/24 - 28/03/24
Inner System Integration
26/07/21 - 05/12/23
Inner System Insertion into ITK
29/03/24 - 09/05/24
Design optimization
PDRs
FDRs
Pre-prod
Local supports PRR
13/11/19
FE chip PRR
13/11/19
Planar Sensor PRR
30/04/20
Hybridization PRR
30/09/20
Outer Barrel Ready
27/11/23
Outer System Ready for
insertion into ITK
22/01/24
Pixel Detector
Integrated in ITK
09/05/24
ITK Ready for
installation Date
01/04/25
+ 2 mo

Trigger schemes