Pixel Sensor Development for the ATLAS ITk Upgrade

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on behalf of the ATLAS-ITk Pixel collaboration

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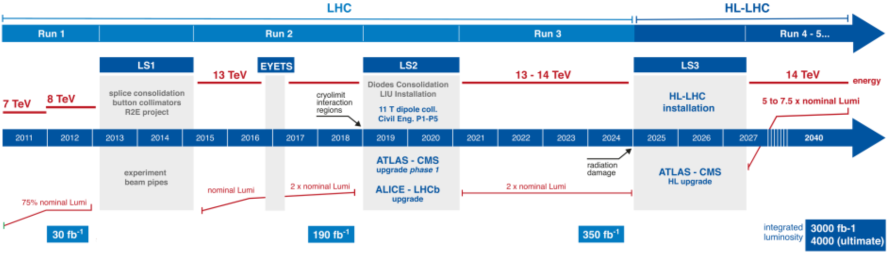
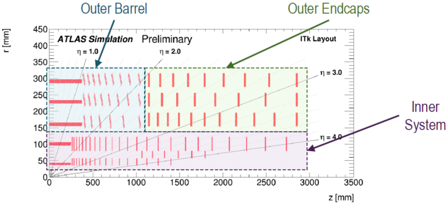
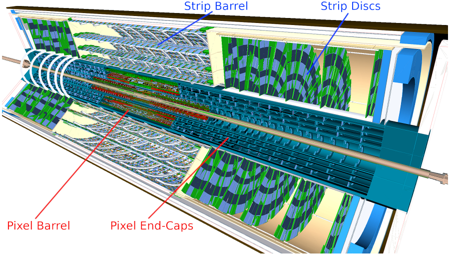
LHC Upgrade

- LHC will be upgraded to High-Luminosity (HL-LHC)
- $\approx 60 \rightarrow 200$ interactions per bunch crossing
- Current inner detector must be upgraded to satisfy new requirements



The ITk Detector





ATLAS ITk Pixel TDR, CERN-LHCC-2017-005

Inner Detector (ID) will be replaced by full-Si Tracker (ITk):

- Coverage up to 4 η with at least 9 points per track
- Outer Part: Si-strip detectors:
  - 4 barrels, 6 endcaps
- Inner Part: 5 layers of **Si-pixel detectors** (covered in this talk):
  - Inner layer (L0): 1188 3D sensors (150 μm), 34 mm from beam
  - Outer layer (L1): 1200 planar sensors (100 μm)
  - Outer barrel and endcap (L2-4): 6816 planar sensors (150 μm)

Current pixel system

~1.9 m^2 of active area

2000 modules

92 Mega-pixels

➤

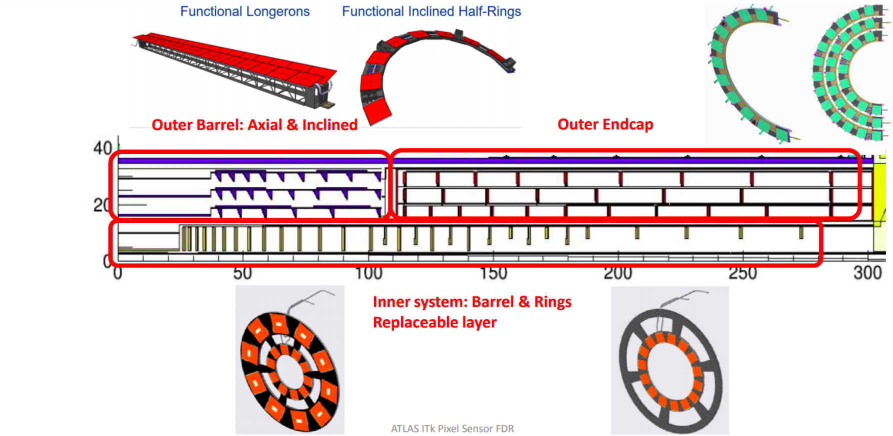
New ITk pixel system

~13 m^2 of active area

9400 modules

1.4 Giga-pixels

Support



ATLAS ITk Pixel Sensor FDR

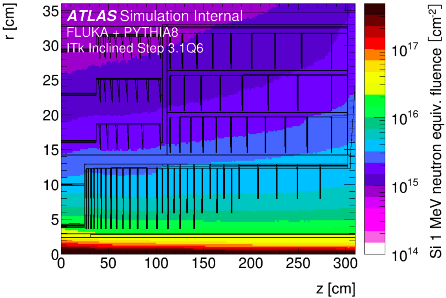
Requirements

Necessary properties:

- Radiation hardness
  - Up to $\approx 2 \times 10^{16}\ \frac{\text{neq}}{\text{cm}^2}$ (3D at L0)
  - Up to order of 10^7 Gy total ionizing doze (TID)
- Increased pileup
  - Up to 10 times more track density
  - Higher granularity
  - Higher burden on readout

Desired for physics:

- High spacial resolution
- High single-pixel hit efficiency



Planar sensor radiation requirements:

Layer	max. fluence n_{eq}/cm^2 (SF=1.5)	max. TID in MGy (SF=1.5)
L1 (@2000fb^{-1})	4.1e15	3,4
L2	4.7e15	5,2
L3	3.2e15	2,5
L4	2.4e15	1,4

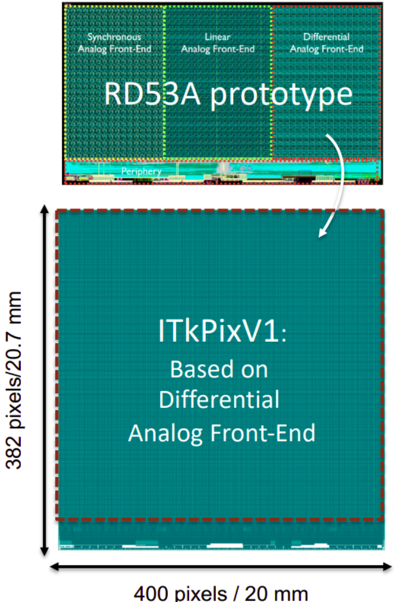
Front End Chip

RD53A prototype:

- Common R&D by ATLAS & CMS
- 50 × 50 μm grid
- Three analog FE

ITkPixV1/2 full size chip:

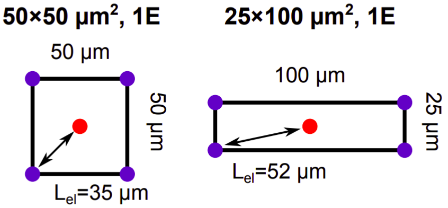
- Based on differential FE
- 1 MHz trigger rate
- Radiation hard up to > 5 MGy ($10^{16}\ \frac{\text{neq}}{\text{cm}^2}$)
- 65 nm technology
- First wafers of V1.1 available
- Final submission of V2 forseen before end of 2021

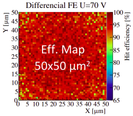


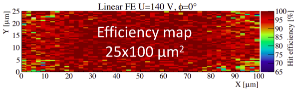
3D sensors

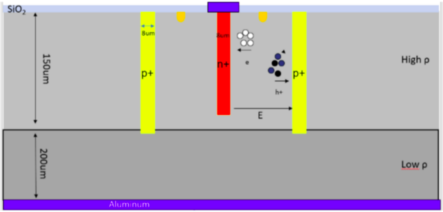
Innermost layer L0 equipped with 3D sensors:

- Final design review (FDR) held 26 Nov 2019
- Proximity to beam requires superior radiation hardnes ($10^{16}\,\frac{\text{neq}}{\text{cm}^2}$)
- L0 replaceable after high irradiation damage
- Triplet module geometry
- Single-side technology (n&p electrodes etched from same side)
- 50×50 (rings) and $25 x 100$ μm^2 (barrel) pixel size
- $> 97\%$ hit efficiency at 14° incl. ($> 96\%$ perpendicular)







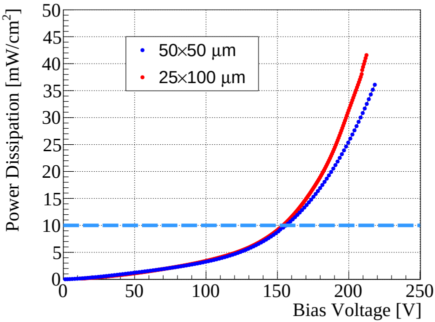


3D sensors

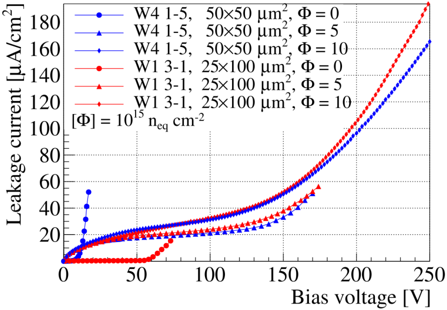
- Low 80 – 140 V bias voltage
- Low power dissipation $< 10\ \frac{\text{mW}}{\text{cm}^2}$ ($@-25\ ^\circ$C, $10^{16}\ \frac{\text{neq}}{\text{cm}^2}$)
- More results for 3D sensors in 3D session on Thursday:
  - By Alessandro Lapertosa on FBK sensors
  - By Stefano Terzo on CNM sensors

Results for CNM sensors on RD53A:

power dissipation ($@10^{16}\ \frac{\text{neq}}{\text{cm}^2}$)



leakage current

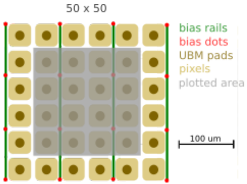


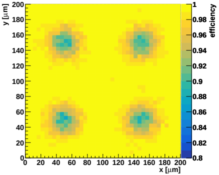
(Nuclear Instruments and Methods in Physics Research Section A, Vol 982)

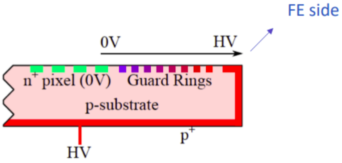
Planar Sensors

Layers L0-4 equipped with planar sensors:

- Final design review (FDR) held 18 Sep 2020
- Outer layer (L1): 100 μm thickness
- Outer barrel and endcap (L2-4): 150 μm thickness
- Pixel size of 50x50 μm^2
- L2-4 expected to survive full amount of irradiation corresponding to 4000 fb^{-1}
- L1 replaced once ($\rightarrow$ 2000 fb^{-1})





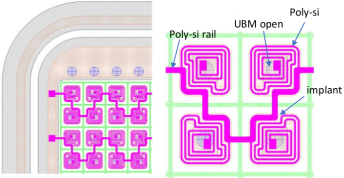


Planar Sensors

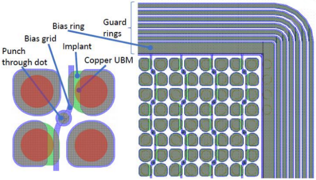
Bias structure allows check of leakage current before flip-chip:

- Several options from different vendors:
  - Poly-silicon bias resistor
    - Higher noise
  - Bias rail with punch-through (PT)
    - Reduced hit efficiency around PT dots
  - No bias structure
    - Needs temporary metal layer until wafer dicing
    - Uniform efficiency
    - No uniform ground in case of disconnected pixel

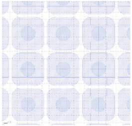
Poly-si bias resistor



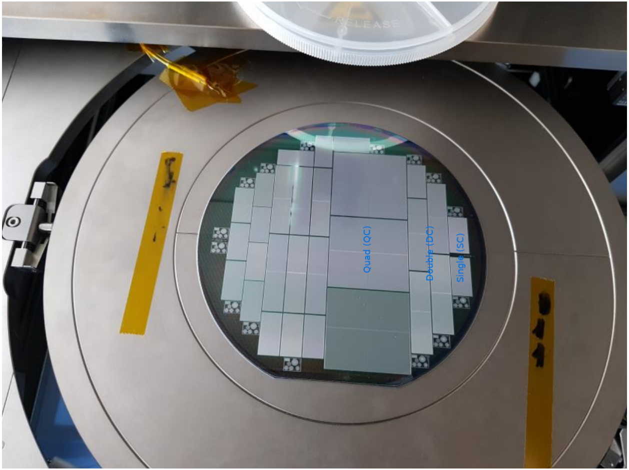
PT dot & bias rail



No bias structure



Planar Sensors

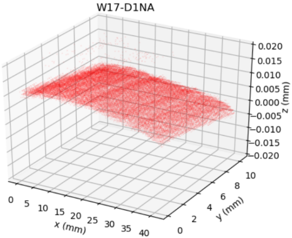


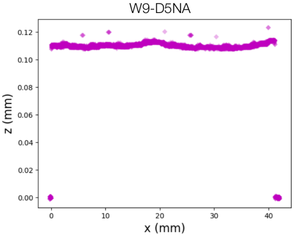
Single (SC), Double (DC), and Quad (QC) layouts

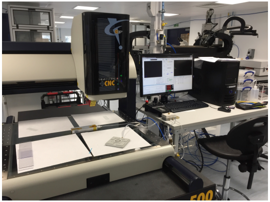
- Prototypes from various different foundries tested
- Final modules will all be quads

Thickness and Planarity

Some institutes have dedicated setup to perform laser scan

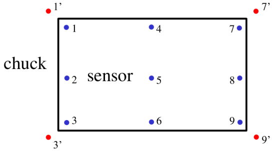






Other institutes: Microscope-focus method:

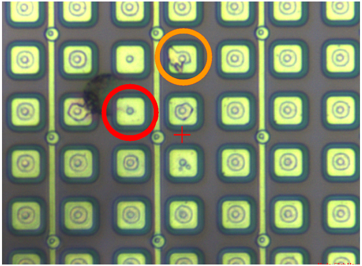
- Focus on several points on sensor and chuck by adjusting microscope height with fixed focal length
- Local thickness approximated as difference of height h between point on chuck and sensor



$$\text{thickness} = \langle h_i^{\text{sensor}} - h_i^{\text{chuck}} \rangle_{i\in[1,9]}$$

$$\text{planarity} = \frac{h_4 + h_5 + h_6}{3} - \frac{h_1 + h_2 + h_3 + h_7 + h_8 + h_9}{6}$$

Visual Inspection

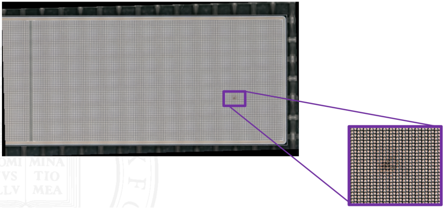


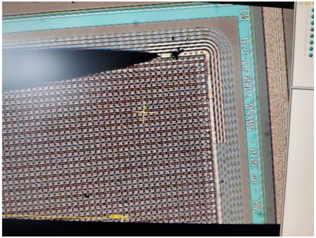
Visual inspection requirements:

- No stains, residues, scratches
- No chips $> 40\ \mu$m at edges
- No shorts between pixels

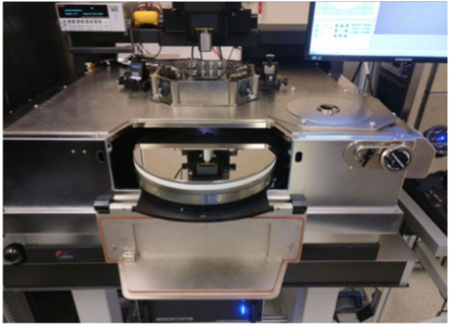
Results:

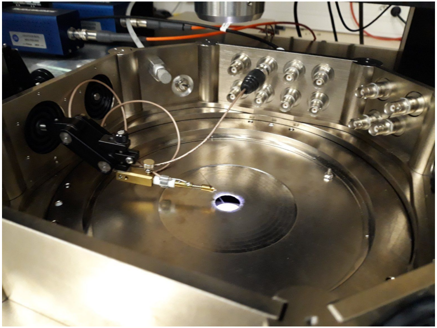
- Most sensors show no visual defects, some exceptions





Electrical Characterization

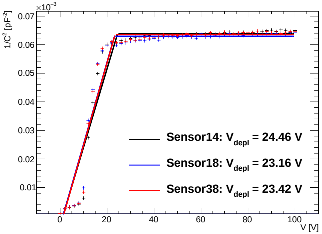


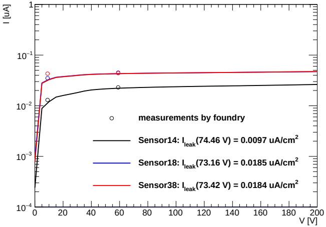


Requirements for Qualification:

- Depletion voltage $V_{\text{dep}} < 100$ V (for 150 μm sensors) measured at 1 kHz
- Leakage current $I_{\text{leak}} < 0.75\ \mu\text{A/cm}^2$ at $V_{\text{dep}} + 50$ V
- Variation of leakage current $\Delta I_{\text{leak}} < 25\%$ measured over 48 h
- Breakdown voltage $V_{\text{break}} > V_{\text{dep}} + 70$ V
  (V_{break} defined as V at which I_{leak} increases by $> 20\%$ over $\Delta V = 5$ V step)

CV and IV





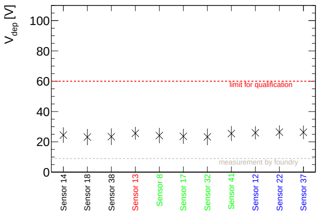
CV measurements:

- Plot $1/C^2$ vs V to calculate V_{dep}
- Perform 2 fits:
  - Constant in fully depleted region
  - Linear rise before
- V_{dep} given by the position of the intersection
- Requirement: $V_{\text{dep}} < 100V$ (for 150 μm)

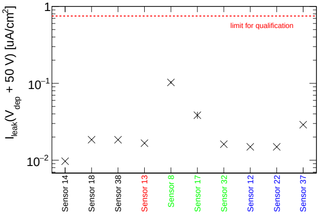
IV measurements:

- Plot I vs V
- Increase by $\Delta I > 20\%$ over $\Delta V = 5V$ step defined as breakdown
- Requirement: $V_{\text{break}} > V_{\text{dep}} + 70$ V
- Requirement: $I_{\text{leak}}/\text{area} < 0.75\ \mu A/\text{cm}^2$ at $V_{\text{dep}} + 50$ V

CV and IV



50x50 single 100x25 single 50x50 double 100x25 double



50x50 single 100x25 single 50x50 double 100x25 double

CV measurements:

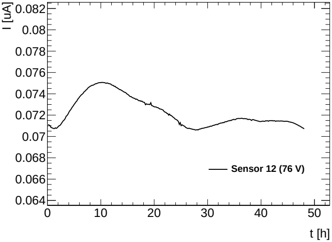
- Plot $1/C^2$ vs V to calculate V_{dep}
- Perform 2 fits:
  - Constant in fully depleted region
  - Linear rise before
- V_{dep} given by the position of the intersection
- Requirement: $V_{\text{dep}} < 100 V$ (for 150 μm)

IV measurements:

- Plot I vs V
- Increase by $\Delta I > 20\%$ over $\Delta V = 5 V$ step defined as breakdown
- Requirement: $V_{\text{break}} > V_{\text{dep}} + 70$ V
- Requirement: $I_{\text{leak}}/\text{area} < 0.75\ \mu A/\text{cm}^2$ at $V_{\text{dep}} + 50$ V

Leakage Current Stability

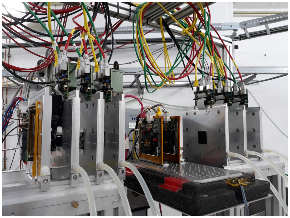
It (48 **h**) $V = V_{\mathbf{dep}} + 50$ **V**

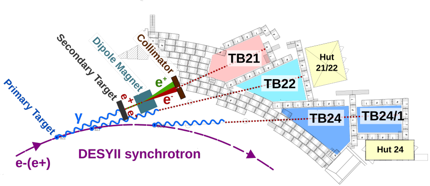


It measurements:

- Plot I at $V = V_{\text{dep}} + 50$ V
- Measure for 48 h
- Ensure stable humidity, temperature, and darkness
- Requirement: Variation $\Delta I_{\text{leak}} < 25\%$

Beam Tests





Hit effiecincy measurements at DESY test beam facility:

- Modules: Planar sensor bump-bonded to RD53 front end chip
- Unirradiated and irradiated to two fluences
- 3 measurement campaigns at DESY: Sep and Nov 2019, Jun 2020
- At least one measurement per vendor per fluence per thickness

Requirements on sensor efficiency:

	Measurement voltage	Fluence	Hit Efficiency
100 and 150 um thickness	Vdepl+50V	Before irradiation	>98.5%
100 um thickness	300V 400V	F=2x10^{15} n_{eq}/cm^2. F=5x10^{15} n_{eq}/cm^2,	>97%
150 um thickness	400V 600V	F=2x10^{15} n_{eq}/cm^2, F=5x10^{15} n_{eq}/cm^2,	>97%

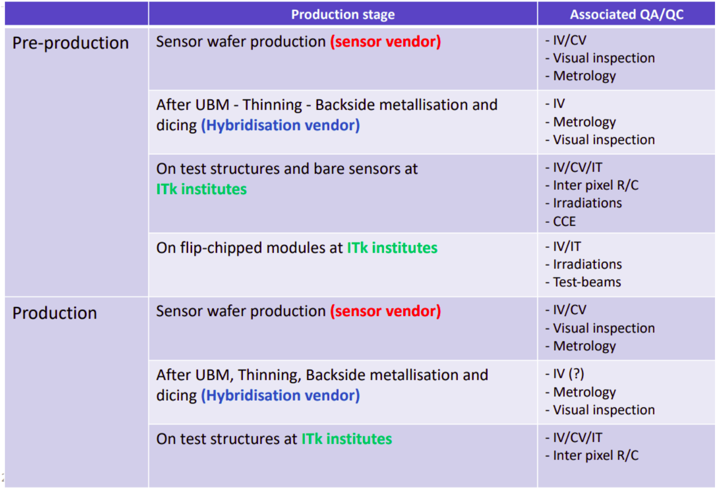
QA/QC

Quality Control (QC):

- Identify defects in finished sensors

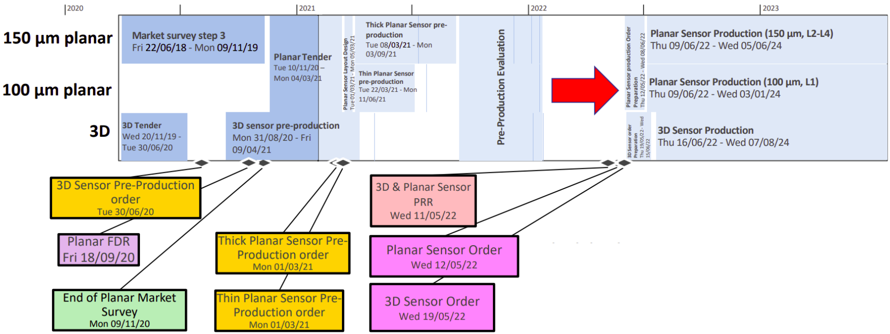
Quality Assurance (QA):

- Prevent defects in production



	Production stage	Associated QA/QC
Pre-production	Sensor wafer production **(sensor vendor)**	- IV/CV - Visual inspection - Metrology
	After UBM - Thinning - Backside metallisation and dicing **(Hybridisation vendor)**	- IV - Metrology - Visual inspection
	On test structures and bare sensors at **ITk institutes**	- IV/CV/IT - Inter pixel R/C - Irradiations - CCE
	On flip-chipped modules at **ITk institutes**	- IV/IT - Irradiations - Test-beams
Production	Sensor wafer production **(sensor vendor)**	- IV/CV - Visual inspection - Metrology
	After UBM, Thinning, Backside metallisation and dicing **(Hybridisation vendor)**	- IV (?) - Metrology - Visual inspection
	On test structures at **ITk institutes**	- IV/CV/IT - Inter pixel R/C

Schedule



Planar sensors:

- Pre-prod.: Mar - Sep 2021
- Production: mid 2022 - mid 2024

3D sensors:

- Pre-prod.: Aug 2020 - Apr 2021
- Production: mid 2022 - mid 2024

Conclusion

ATLAS Inner Detector will be replaced with full-Si ITk:

- Full-size ITkPixV1 front end chip based on RD53A prototype
- 1188 3D sensors at high-radiation inner layer
    - Pre-production started
    - 50×50 μm and 25×100 μm layout
- 8016 planar sensors in outer layers
    - 50×50 μm layout
    - Extensive Market Survey to qualify vendors
- Production for both sensor types forseen for mid 2022 - mid 2024
- QA/QC ongoing during pre-production and production
- Both type of sensors demonstrated necessary requirement for ITk