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The performance and operational experience of ATLAS Semiconductor Tracker in Run-2 at LHC

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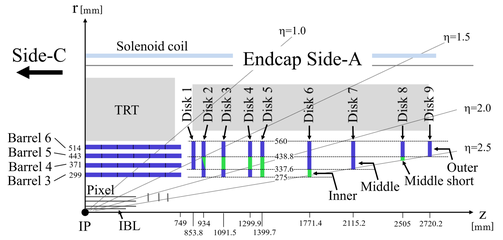
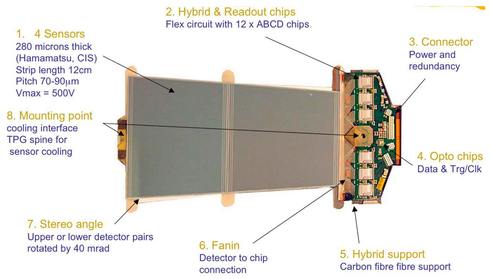
The Run 2 at LHC

Results from *pp* Run 2 (2015-2018): 156 fb-1 @ 13 TeV. Peak luminosity: $2 \cdot 10^{33}$ cm^{-2}s^{-1}.

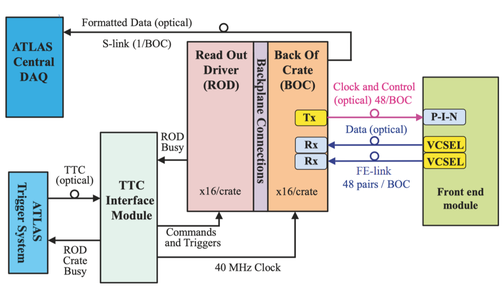
Twice the design LHC luminosity: **higher pileup**, up to ~60 *pp* interactions per events possible instead of 23, leading to up to **~2% hit occupancy** (SCT design 0.2-0.5%).

The semiconductor tracker (SCT)



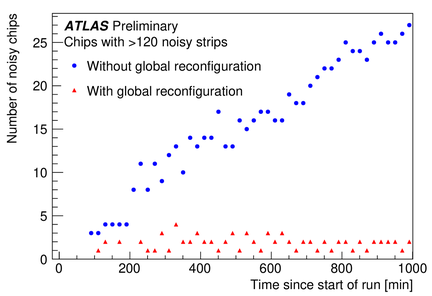


Component	Total	Barrel		Endcaps		SCT		Fraction [%]	
Modules	4088	12	(11)	30	(19)	42	(30)	1.0	(0.73)
Chips	49056	55	(38)	22	(17)	77	(55)	0.16	(0.11)
Strips	6279168	6398	(4111)	9505	(7252)	15903	(11363)	0.25	(0.18)



A **Global Reconfiguration** to the entire SCT DAQ takes 1.2 seconds, recovering desynchronized modules getting noisy.
It is regularly applied during data taking, for negligible data loss.

Average **SCT deadtime in Run 2: <0.1%**.



Data Acquisition (DAQ)

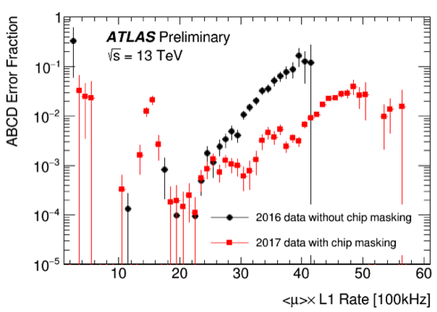
Need to overcome bandwidth limitations.

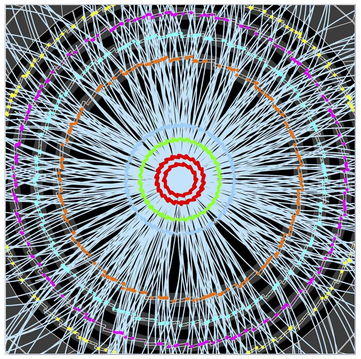
S-links Expanded from 90 RODs w/ 48 modules → to **128 w/ 36** modules

Cable Remapping: limit data load on each ROD to get a flatter occupancy distribution across S-links.

Data Compression: veto hits from preceding bunch crossing ("01X" read mode).
Up to 16 strips clusters packed into a single 16-bit word: **~25% data size reduction**.

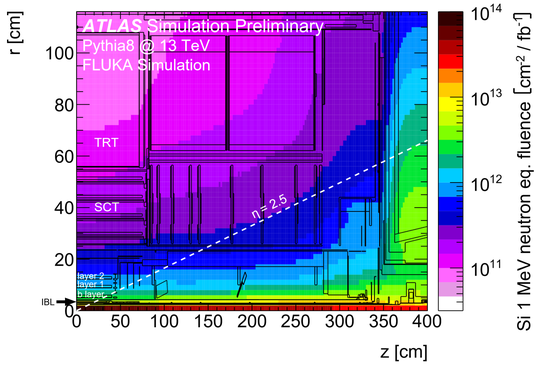
High pileup causes chip errors and makes modules noisy, increasing bandwidth use. Implemented **Chips Masking** during operation, recovering modules on the fly when pileup conditions improved.





Radiation Damage

Effect of radiation damage on the modules: number of donors decreases, acceptors increases → **Type Inversion** from *n*-bulk into *p*-bulk material, expected around second half of Run 2. Taken into account in the design, built to endure up to 700 fb^{-1} @ 14 TeV.



Agreement between simulation (figure above and table below) and dedicated radiation monitoring systems:
- Total ionising dose (TID) → *p*-MOSFET transistors
- Non-ionising energy loss (NIEL) → *p-i-n* diodes

Total fluence:
5.6 ·10^{13} 1 MeV equivalent thermal neutrons.

$\lvert\eta_{\text{index}}\rvert$	z [mm]	Barrel 3 (r = 299 mm)	Barrel 4 (r = 371 mm)	Barrel 5 (r = 443 mm)	Barrel 6 (r = 514 mm)
1	61.9	4.30	3.41	2.85	2.45
2	184.0	4.37	3.46	2.87	2.47
3	308.7	4.47	3.51	2.92	2.52
4	431.2	4.53	3.58	3.00	2.57
5	555.3	4.65	3.71	3.09	2.66
6	679.1	4.80	3.84	3.20	2.76

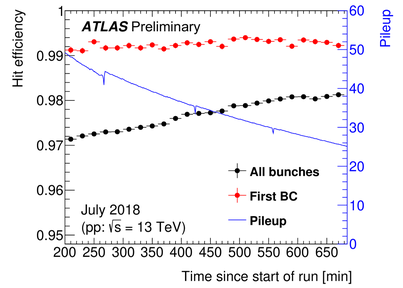
Disk	z [mm]	Inner (r = 304.6 mm)	Middle (r = 396.5 mm)	Outer (r = 499.4 mm)
1	853.8	–	3.86	3.07
2	934.0	5.12	3.89	3.08
3	1091.5	5.20	3.98	3.19
4	1299.9	5.27	4.14	3.31
5	1399.7	5.37	4.21	3.40
6	1771.4	5.69	4.47	3.67
7	2115.2	–	4.94	4.01
8	2505.0	–	5.74	4.66
9	2720.2	–	–	5.33

Performance

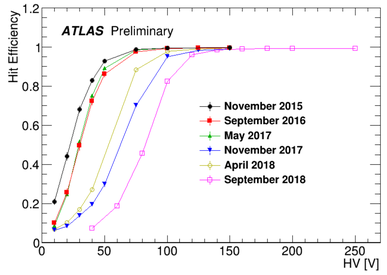
Hit Efficiency for a track with $N_{cluster}$ and N_{hole} associated defined as

$$\varepsilon = \frac{N_{\text{cluster}}}{N_{\text{cluster}} + N_{\text{hole}}}$$

Affected by the "01X" read mode: real hit lost, if present in preceding bunch.
Negligible impact on tracking (1% hit loss).

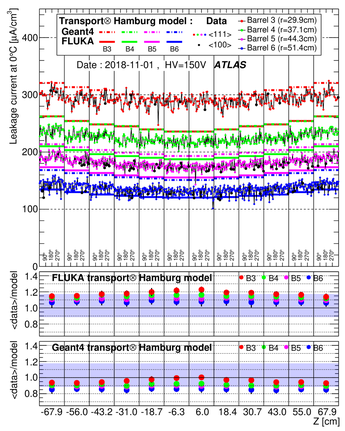


Pileup affects hit efficiency (left). The **intrinsic hit efficiency** (**~99%**) obtained by the first bunch in a train.



After type inversion, increase in efficiency with HV was slower (left). **Operational HV** was therefore **increased**.

Leakage Current is thermally generated electron-hole pairs. If too large, might cause thermal runaway, forcing to lower HV, hence reducing the hit efficiency.



Normalised **leakage currents** per unit volume for all barrel modules (above) during Run 2 show **consistent I_{leak} within ~3%**.

Over the course of Run 2 it **increased ten fold** in agreement with predictions **within 30% uncertainty**.

Calibration

Goal: Maintain hit efficiency >99% and **noise occupancy < 5x10^{-4}**. Methods:
- Analogue optimisation
- Trim range scan
- Response curve
- Optical
- Digital tests

Full Calibration Time: **1.5 hours**, typically every few weeks.

Noise levels increased by 10-20%.
Still sufficiently low compared to the **threshold of 1 fC**.

Conclusion

SCT operated stably throughout Run 2, with several new improvements: additional RODs and BOCs, more aggressive data compression, automatic recovery mechanisms for modules and RODs, improved cooling, calibration time reduced.

Leakage current and **Full Depletion Voltage** are accurately monitored, and more results are not listed here.

Available for 99.9% of integrated luminosity, achieved a **data quality efficiency of 99.85%**, thanks to the low **noise occupancy**, kept **below 5x10^{-4}** and high **hit efficiency ~99%**.

Safe and stable operation is expected until end of Run3, with an integrated luminosity of ~200 fb-1 with similar pileup levels.

Reference:
To be published.

"**Operation and performance of the ATLAS semiconductor tracker in LHC Run 2**".