Inner Detector Tracker Advances

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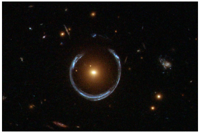
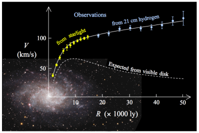
TRIUMF

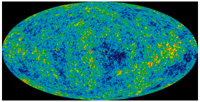
Future Needs of Inner Trackers
ATLAS Upgrade
Strip Technology
Pixel Technlogy
Further into the future

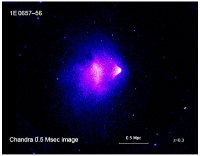
Future Needs of Inner Trackers

- Higgs completes the Standard Model
- But we know there is more:
  - Dark Matter
  - Hierarchy/Naturalness/... problems
  - Neutrinos are not massless (Oscillations)
  - Dark Energy
- The LHC experiments search for more, and are ruling out swathes of parameter space
- Amassing a bigger data set will further push these limits, or make discoveries
- Future e+/e- machine (ILC, CLIC, ...)
  - Precision measurements of Higgs parameters
  - Any deviation from SM prediction implies new physics
- Large inner trackers with very low radiation length needed









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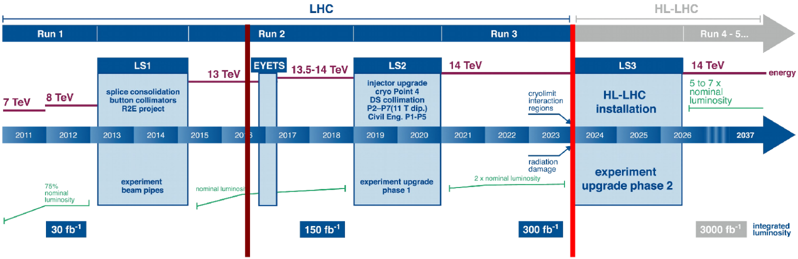
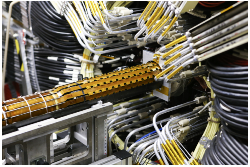
LHC Upgrades

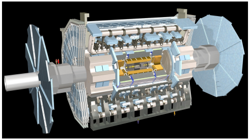


- Several running periods interspersed with longer shutdowns
- In each shutdown the LHC will increase in instantaneous luminosity
- Starting 2026, the High-Luminosity LHC will deliver 7 times the design luminosity of 1×10^{-34} cm^{-2}s^{-1}
    - HL-LHC will deliver upto 300 fb^{-1} per year
    - Upto 200 interactions per bunch crossing
    - Around 6000 tracks per b.c. in the inner detector
- The goal is to deliver 3000 fb^{-1} in ≈ 10 years.

ATLAS Upgrades

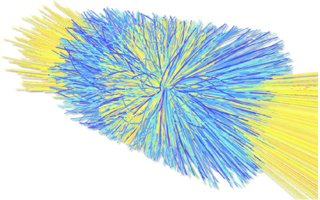
- In LS1 ATLAS installed a new inner-most pixel layer "IBL", inside the previous one
  - Improved vertex measurements, enhancing analyses involving b-quarks
  - Includes 3D silicon sensors, more later
- LS2:
  - New muon chambers in the forward region, the New Small Wheels
    - A mixture of micromegas and thin gap gaseous detectors
    - better triggering; muon momentum threshold can stay low despite the luminosity increase
  - New calorimeter electronics, all data read out, triggering off-detector
  - Many other improvements in the trigger to cope with the higher luminosity
- LS3: Completely new Inner Tracker, the ITk.
- CMS has a similar programme.



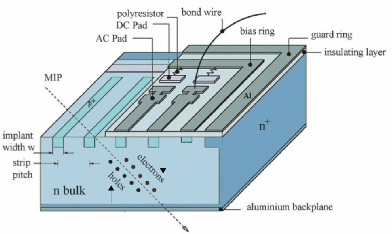


Why an entirely new ITk?

- At 7×10^{34} cm^{-2}s^{-1}, the current straw tube system TRT will be overwhelmed
- The current strip detector, SCT, starts to drop data at 3×10^{34} cm^{-2}s^{-1}
- Both the pixel and SCT will age rapidly through radiation damage
- Average occupancy in the SCT will be high, leading to difficulties in tracking



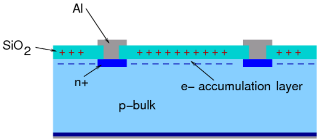
What's wrong with p-in-n?

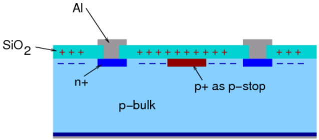


- Current ATLAS SCT uses p strips in n doped substrate
  - Cheap to produce, works well with the doses expected before HL-LHC
  - Radiation damage: substrate turns to p-type
  - Junction moves to the back plane with n+ implant
  - Depletion zone grows from there to the p-strips: requires full depletion (high HV)
  - Otherwise signal drops off rapidly as the non-depleted region grows
  - Insufficiently rad-hard for HL-LHC.
- Solutions:
  - n+ in n: expensive, double side processing
  - n in p: chosen for ITk

New for ATLAS Strips: n-in-p Sensors

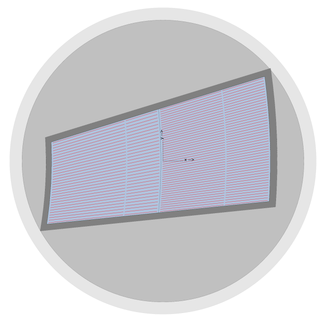
- Need for p-stop or p-spray isolation between strips:
    - The SiO_2 layer builds up +ve charge
    - This attracts a layer of e- just below it
    - This dipole gives high capacitance between strips
        - High noise and signal sharing between strips
    - Surrounding each strip by a p+ implant interrupts these electrons giving good interstrip isolation
    - Many p-stop layouts prototyped for optimisation of ATLAS sensors





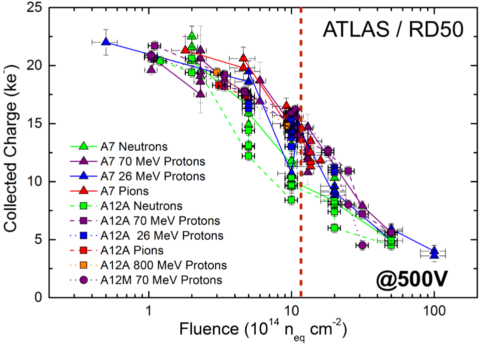
Other new developments for ATLAS Strips

- 150 mm wafers reduce the number of components cf SCT 100 mm wafers
- Multiple rows of strips per sensor:
  - Reduced occupancy
  - Less capacitance so less noise
  - Maintains signal to noise in presence of radiation damage
- Novel endcap sensors to fill endcap wheels
  - Arcs of circles, inner and outer edges
  - Side edges twisted by 20 mrad stereo angle to accommodate built-in stereo in strips
  - Varied pitches to fit readout chips
- Care in design and cutting allows high bias voltages (up to 1000 V)
  - Less signal loss in traps
  - Higher radiation hardness

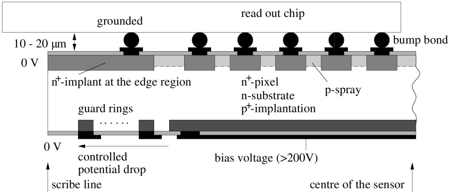


Radiation Hardness of ATLAS Sensors

- Many sensors, both full-size and miniature, have been irradiated to levels beyond HL-LHC
- Neutron, pion, proton...
- Performance after irradiation remains good
  - S/N > 10
- Leakage current low provided the detectors are run cold (-20 °C)
  - CO_2 evaporative cooling



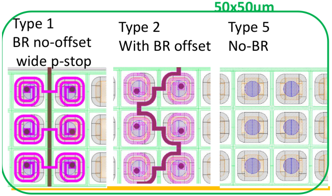
Planar Pixels



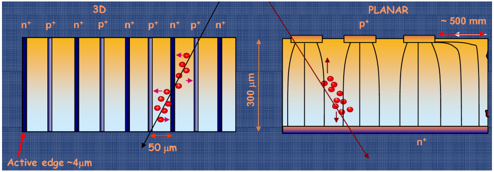
- Pixel advantages over strips:
  - 2D info in a single detector: no ghosts, similar material cf. two strip layers
  - Small diode size: high position resolution, low capacitance/noise so very rad hard
  - Low occupancy, less confusion in tracking
- As used in current ATLAS and continues as part of base-line for future ATLAS upgrades
- Issues with leakage current leading to possibly excessive heat production
- Reliable and understood, but costly (separate sensor and read-out chip, bump bonding)
  - Limits the extent of pixels that can be afforded

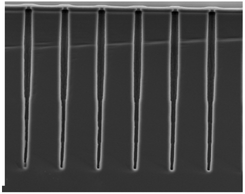
Planar Pixel Miniaturisation

- Small is beautiful: better resolution, lower occupancy, separate tracks in high density jets
- Current ATLAS pixels 50 μm x 400 μm. Limited by readout electronics.
- Going from 250 nm to 65 nm readout-chip technology allows smaller pixels
- Develop 50 x 50 and 25 x 100 μm^2 pixel sensors
  - Edge effects more critical
  - Field effects of bias rail etc. need care
- Also develop designs with narrow guard rings to reduce dead area between sensors



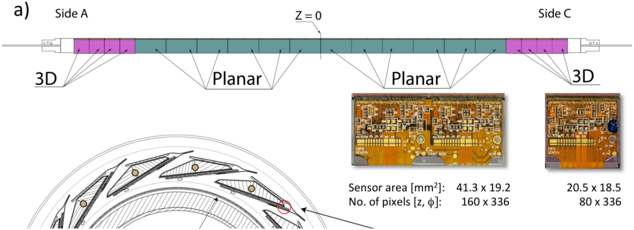
3D Pixels





- In planar sensors, charge drifts the entire thickness of the sensor
- Initial drift signal spreads over several pixels, and after radiation damage gets lost in traps
- Can thin the planar sensor for lower voltage, but you are losing signal
- 3D sensors keep full signal while reducing trapping and heat production
- Made possible with Deep Reactive Ion Etching (DRIE)

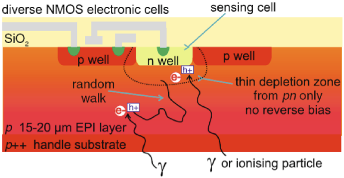
3D in ATLAS IBL



- Used in ATLAS IBL, new (2015) innermost pixel layer
- And in very forward ATLAS detectors (AFP)
- Helps solve over-heating problem at HL-LHC

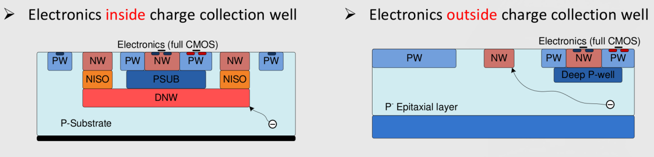
MAPs Detectors

- Drive to lower costs:
  - Use industry standard processes
  - Use the CMOS itself as sensor:
    - No sensor cost
    - No bump-bonds
- Monolithic Active Pixel devices: charge liberated in a CMOS chip is amplified in that same chip
- Initial designs had no drift field; signal diffuses to junction
  - Slow
  - Not rad-hard: plenty of time to fall into traps



Evolution of Silicon Sensor Technology in Particle Physics,
F. Hartmann, Springer Volume 231, 2009

CMOS Pixels



T. Wang, Bonn

- Recent industry developments allow drift field to be applied across the signal region
- Up to 40 V across 40 μm
- Fast and rad-hard
- Two approaches:
  - Amplifier + disctriminator + signal region in the CMOS; discriminated signal picked up in high-speed digital chip via capacitive transmission: glue chips together, no bumps
  - Fully monolithic: Digital-MAPs, high speed digital circuitry also in the detector+analogue layer

Digital-MAPs

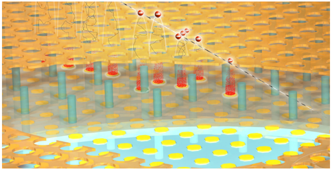
- Clearly DMAPs is preferred, but is challenging
  - Must isolate high-speed digital from the small signal part
  - Want fully active area: collect charge from below the digital part
  - Tends to increase capacitance hence noise
  - Use deep-well technologies and careful separation of power/ground to isolate digital/analogue
- Many groups designing and producing prototypes in various technologies
- Race against time to find a good solution for ATLAS at HL-LHC

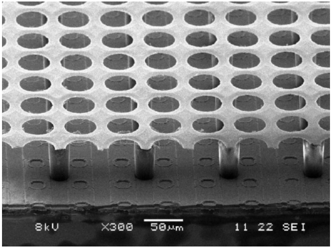
Quick glimpse further into the future

- Micro Electro-Mechanical Systems (MEMs) and nano-technologies allow us to build up structures on top of pixel read-out chips
- Novel detectors with gas or thin solid layers in vacuum possible

Gaseous detectors using MEMS

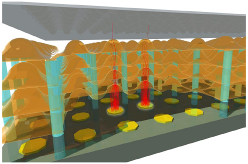
- Build an electrode grid 50 μm above the readout chip supported on pillars positioned between the pixels
- Large drift-space above grid: electrons liberated by charged particles sucked through the grid holes
- High E-field below grid gives electron multiplication — sufficient signal to trigger the pixel
- Drift time gives third coordinate: vector track segments within a single detector layer
- Current precision on position of each electron approaching 20 μm in each of (x, y, z)
- Track position precision < 10 μm

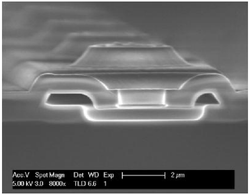




Picosecond Photon Counters

- Pico second timing becomes very interesting
- Speed of light is 0.3 mm/ps, less than separation of pile-up vertices at ATLAS
- SiPM now in tens of ps
- Tipsy project aims further
  - Use nanotechnology and understanding of surface science to produce transmission dynodes
  - Electrons impingeing from above knock out several electrons from bottom side
  - Domed structure focusses these to the next layer
  - Several layers produce sufficient signal for the pixel readout chip
  - Total process is over in about 2 ps; with new electronics can imagine genuine ps timer





Summary

- LHC upgrades and future colliders will need inner trackers going beyond what we have today
    - Square meters, number of channels, radiation damage, radiation length...
    - There is a lot of room for creativity and innovation
- ATLAS Upgrade for 2026 has strip detectors demonstrated to meet the needs, and an array of possible pixel technologies
- Looking further ahead, current advances in CMOS chip industry and MEMS/nanotechnology promise further improvements