Outline

Lecture 1
1. Interaction of charged particle with matter
2. Momentum measurement
3. Drift and Diffusion in Gases
4. History of Tracking Detectors
5. Proportional Chambers

Lecture 2
6. Drift Chambers
7. Micro Pattern Gas Chambers
8. Limitations of Gaseous Detectors

Lecture 3
9. Vertex Reconstruction
10. Semiconductor Detectors
11. Silicon Strip and Pixel Detectors
12. Radiation Damage of Silicon Detectors
13. New Semiconductor Detector Concepts
14. Tracking Systems: ATLAS, CMS
9. Need for semiconductor tracker: Vertex Reconstruction

\[ B_s^0 \rightarrow \psi' (\rightarrow \mu^+ \mu^-) \phi (\rightarrow K K) \]

Aleph event:
Fully reconstructed \( B_s \) decay.

Track measurements with a precision of a few \( \mu m \) near the interaction point improve the momentum measurement and allow to determine the decay vertex, especially important for bottom hadrons.
The life time of B-mesons can be measured from the decay length \( l \), if the momentum of the B-meson (\( \gamma \)-factor) is measured as well. 

\[
l = \gamma c \tau_B \approx \gamma \cdot 500 \, \mu m
\]

\[
\tau_B \approx 1.6 \, ps
\]
Impact parameter resolution (simplified)
Impact parameter resolution (simplified)

\[ \sigma_b \sim \frac{r_1}{\sigma_2} \quad \text{small} \]

\[ \sigma_1 = \frac{r_2}{r_2 - r_1} \quad \text{small} \]

\[ \sigma_2 = \left( \frac{r_1}{r_2 - r_1} \sigma_2 \right)^2 + \left( \frac{r_2}{r_2 - r_1} \sigma_1 \right)^2 + \sigma_{MS}^2 \]

\[ \sigma_{MS} \sim \frac{1}{p} \sqrt{\frac{x}{X_0}} \]

small x/X_0
... and ... vertexing at LHC

\[ \text{pp} \rightarrow \text{ttH (m=120 GeV)} \]
\[ \text{H} \rightarrow \text{bb} \]
\[ \text{tt} \rightarrow \text{W(lvl)b W(qq)b} \]

\sim 1200 \text{ tracks/BX}

high track density
in particular in jets

3D hit information
mandatory

pixels
Silicon and germanium have 4 valence electrons, thus four covalent bounds. Thermal excitation excites electrons to the conduction band, which creates holes in the valence band.

**Intrinsic electron(hole) concentration:** \( n_i = A T^{3/2} \exp(-E_g/2kT) \)

(Si: Energy gap \( E_g = 1.12 \text{ eV} \), Ge: \( E_g = 0.66 \text{ eV} \), \( T = 20 \degree \text{C} \Rightarrow kT = 1/40 \text{ eV} \))

**Typical values at** \( T = 300 \text{ K} \) (compare to silicon concentration of \( 5 \times 10^{22} \text{ cm}^{-3} \))

- Si: \( n_i = 1.5 \times 10^{10} \text{ cm}^{-3} \)
- Ge: \( n_i = 2.5 \times 10^{13} \text{ cm}^{-3} \)
10. Signal from Ionizing Particle

Comparison for T=300 K and a pure Si volume shown on the right.

4.5 x 10^8 intrinsic e-h pairs

3.2 x 10^4 e-h pairs produced by M.I.P. (minimal ionizing particle)

Conclusion:
Signal too small. Need to reduce free charge carriers, i.e. deplete the detector.

Use doped semiconductors to create reversed bias depleted p-n junction.
10. Doped Semiconductors (1)

n-type silicon
- Si has 4 valence electrons
- add elements from Vth group (5 valence electrons)
- donors (phosphorous, arsenic) give away one electron.
- creates high energy level of electrons
- small thermal excitation (0.05 eV for Si) needed to increases electron concentration in CB.
- n-type: electron concentration $n$ larger then hole concentration $p$.

$p \approx N_A$ ($N_A = \text{acceptor concentration}$)

p-type silicon
- Si has 4 valence electrons
- add elements from III-rd group (3 valence electrons)
- acceptors (boron, Indium, gallium...) misses one electron
- creates discrete energy level for holes
- small thermal excitation needed to increases hole concentration in VB.
- p-type: holes are the majority carriers.
Typically one uses a very small concentration of dopants.

Silicon concentration: \(5 \times 10^{22}\) atoms/cm\(^3\)

Typical dopant concentration: \(5 \times 10^{13}\) atoms/cm\(^3\)

Heavily doped material used for electrical contacts (indicated with +), p+, n+ can be as high as \(10^{20}\) atoms/cm\(^3\).

<table>
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<tr>
<th></th>
<th>detector grade</th>
<th>electronics grade</th>
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</thead>
<tbody>
<tr>
<td>doping</td>
<td>(\approx 10^{12}) cm(^{-3})</td>
<td>(\approx 10^{17}) cm(^{-3})</td>
</tr>
<tr>
<td>resistivity (\rho)</td>
<td>(\approx 5) k(\Omega\cdot)cm</td>
<td>(\approx 1) (\Omega\cdot)cm</td>
</tr>
</tbody>
</table>

Conductivity

Two basic relations: \(np = n_i^2 = AT^3 \exp(-E_g/kT)\) with \(n_i\) = intrinsic carrier concentration

\[N_D + p = N_A + n\] with \(N_D, N_A\) donor/acceptor concentrations

Example: n-type (e.g. \(N_A=0, n \gg p\)) ; analogous result for p-type

majority carrier concentration \(n = N_D\),
minority carrier concentration \(p=(n_i)^2/N_D\)

Conductivity: \(\sigma = 1/\rho = e N_D \mu_e\)

\(\mu_e\) : electron mobility
10. pn-junction

- p-type and n-type regions are neutral
- Electrons diffuse towards p-type and fill holes (recombination).
- Holes drift towards n-type
- Space charge builds up “-” on p-type and “+” on n-type.
- Space charge creates E-field.
- Potential difference exists at junction (contact potential, about 1 Volt).
- Space charge region is depletion zone (devoid of charge carriers). Any e-hole, which is created, will be swept away by the E-field.
10. Depletion Width (1)

**Total charge is conserved:** \( N_A x_p = N_D x_n \)

- **high p doping** \((N_A \gg N_D)\): \( x_n \gg x_p \)
- **high n doping** \((N_D \gg N_A)\): \( x_p \gg x_n \)

Depletion is mainly in lower doped region

Solution of Poisson equation:

\[
  x_n = \sqrt{\frac{2\epsilon\epsilon_0 V_0}{e} \frac{N_A}{N_D} \left(\frac{1}{N_D} + \frac{1}{N_A}\right)}
\]
\[
  x_p = \sqrt{\frac{2\epsilon\epsilon_0 V_0}{e} \frac{N_D}{N_A} \left(\frac{1}{N_D} + \frac{1}{N_A}\right)}
\]

**Depletion width** \( w \):

\[
  w = x_n + x_p = \sqrt{\frac{2\epsilon\epsilon_0 V_0}{e} \left(\frac{1}{N_D} + \frac{1}{N_A}\right)}
\]

**Built-in voltage** \( V \):

\[
  V_0 = \frac{kT}{e} \ln \left(\frac{N_A N_D}{n_i^2}\right)
\]

Example: Silicon pn-junction at room temperature with \( N_A = 10^{16} \text{ cm}^{-3}, N_D = 10^{12} \text{ cm}^{-3} \) gives \( V_0 = 0.458 \text{ V} \)
Depletion Width (2)

For the typical case of very asymmetric doping, i.e. $N_A \gg N_D$, one gets with

$$w = x_n + x_p = \sqrt{\frac{2\epsilon\varepsilon_0 V_0}{e}} \left( \frac{1}{N_D} + \frac{1}{N_A} \right)$$

and

$$x_n = \sqrt{\frac{2\epsilon\varepsilon_0 V_0}{e}} \frac{N_A}{ND(N_A + N_D)}$$

Depletion width

$$w \simeq x_n \simeq \sqrt{\frac{2\epsilon\varepsilon_0 V_0}{eN_D}}$$

Other formulae:

Max. E-Field at junction:

$$E_{max} = \frac{1}{\epsilon\varepsilon_0} eN_D x_n = \frac{1}{\epsilon\varepsilon_0} eN_A x_P \simeq \sqrt{\frac{2e}{\epsilon\varepsilon_0} N_D V_0}$$

Example:

Silicon pn-junction at room temperature with, $N_A = 10^{16}$ cm$^{-3}$, $N_D = 10^{12}$ cm$^{-3}$, $V_0 = 0.458$ V

$W = 25$ µm and $E_{max} = 384$ V/cm
10. Reversed Bias Voltage

Increase depletion width with reversed bias

Electron - hole pairs, created in the depletion region by the ionizing particle, drift in the electric field.

- typical ionization: 100 e-h pairs/µm
- typical noise: 1000 electrons

Large S/N requires large depletion region, i.e. large reverse bias voltage.
## 11. Silicon Strip Detector

**Direct coupling:** reverse current $I_r$ is absorbed by electronics.

**Capacitive coupling:** AC part goes to amplifier, DC part goes through bias resistor $R$.

- **Typical detector thickness:** $300 \, \mu m \ (150 \mu m - 500 \, \mu m)$
- **Typical strip separation, pitch $p$:** $20 \, \mu m - 150 \, \mu m$
- **Position resolution:** $\sigma = \frac{p}{\sqrt{12}} \approx 14 \, \mu m \ (p=50 \, \mu m)$

- Bias resistor produced by deposition of polysilicon.
- Capacitors produced via metal readout lines over implants ($SiO_2$ isolation).

Several different methods are used to readout strips and to provide bias voltage. They are implemented in the manufacturing process.
11. Example: n-strip and p-stop

Diagram showing a cross-section of a detector with labeled regions for n-strip and p-stop.
11. Measured Signal

- **Collected Charge for a Minimum Ionizing Particle (MIP)**

  - **Mean energy loss**
    
    \[ \text{dE/dx (Si)} = 3.88 \text{ MeV/cm} \]
    
    \[ \Rightarrow 116 \text{ keV for } 300 \mu \text{m thickness} \]

  - **Most probable energy loss**
    
    \[ \approx 0.7 \times \text{mean} \]
    
    \[ \Rightarrow 81 \text{ keV} \]

  - **3.6 eV to create an e-h pair**
    
    \[ \Rightarrow 72 \text{ e-h / } \mu \text{m (mean)} \]
    
    \[ \Rightarrow 108 \text{ e-h / } \mu \text{m (most probable)} \]

  - **Most probable charge (300 \mu \text{m})**
    
    \[ \approx 22500 \text{ e} \approx 3.6 \text{ fC} \]

  Most probable charge \( \approx 0.7 \times \text{mean} \)

  Mean charge

  ![Graph of measured Landau distribution in a 300 \mu \text{m thick Si detector.}](from M. Moll)
II. Signal to Noise ratio (S/N)

- **Landau distribution** has a low energy tail - becomes even lower by noise broadening

  **Noise sources:** \( \text{ENC} = \text{Equivalent Noise Charge} \)

  - Capacitance \( \text{ENC} \propto C_d \)
  - Leakage Current \( \text{ENC} \propto \sqrt{I} \)
  - Thermal Noise (bias resistor) \( \text{ENC} \propto \sqrt{\frac{k_B T}{R}} \)

- **Good hits selected by requiring** \( N_{\text{ADC}} > \) noise tail
  - If cut too high \( \Rightarrow \) efficiency loss
  - If cut too low \( \Rightarrow \) noise occupancy

- **Figure of Merit:** Signal-to-Noise Ratio S/N

- **Typical values** >10-15, people get nervous below 10. Radiation damage severely degrades the S/N.

  \( \text{from M. Moll} \)
11. Signal Spread: Charge Collection and Diffusion

**Charge collection time:**
Drift velocity of charge carriers \( v = \mu E \) and drift time \( t_d = \frac{d}{v} = \frac{d}{\mu E} \).

Typical values: \( d=300 \ \mu m, \ E=2.5 \ \text{kV/cm} \) (\( \mu_e=1350 \ \text{cm}^2/\text{Vs} \) and \( \mu_h=450 \ \text{cm}^2/\text{Vs} \)).

Drift times: \( t_d(e) = 9 \ \text{ns}, \quad t_d(h) = 27 \ \text{ns} \)

**Diffusion:**
Diffusion of charge cloud caused by scattering of charge carriers. Width of distribution increases with drift time \( t_d \). Using the diffusion constant \( D = \mu kT/e \) one finds:

\[
\sigma = \sqrt{2Dt_d} = \sqrt{\frac{2dkT}{eE}}
\]

Note that diffusion is the same for electrons and holes, since the mobility drops out.

**Typical charge width:** 8-10 \( \mu m \) in 300 \( \mu m \) thick silicon.
Width of charge cloud could be exploited to obtain better position resolution due to charge sharing between strips (charge centroid finding).
Measurement of Lorentz angle:
Number of strip (or pixel) hits is minimum, if incident angle of beam is equal to Lorentz angle.
Silicon detectors are built at a tilt angle to compensate for the Lorentz angle.

Effective incident angle = tilt angle + Lorentz angle
11. Detector Module: ATLAS Endcap SCT

ATLAS Silicon central tracker SCT

Endcap:
1976 modules with 2 sensors glued back to back on spine.

Rotation by 20 mrad (\(R\phi\) resolution)

Spine conducts heat.

Alignment position of sensors \(\approx 2 \mu m\).

Strip pitch 80 \(\mu m\), width 12 \(\mu m\).

Resolution 16 \(\mu m\) in \(R-\phi\).

Operation temperature \(-7^\circ C\).

99.8\% of strips are working.
Ultrasonic excitation causes vibration of needle. Friction heat welds 25 µm Al wire to metal pad.

Bonding is heavily used in industry, PC processors, but with thicker wires and larger pitch.
11. Connection to electronics

ASICS
11. Hybrid Active Pixel Detector

- **HAPS – Hybrid Active Pixel Sensors**
  - segment silicon to diode matrix with high granularity
    (⇒ true 2D, no reconstruction ambiguity)
  - readout electronic with same geometry
    (every cell connected to its own processing electronics)
  - connection by “bump bonding”
  - requires sophisticated readout architecture
  - Hybrid pixel detectors will be used in LHC experiments:
    ATLAS, ALICE, CMS and LHCb

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[Image of Hybrid Active Pixel Detector diagram]

Flip-chip technique

Solder Bump: Pb-Sn

(from M. Moll)
12. Radiation Damage: Radiation Levels at LHC and SLHC

Example: ATLAS

- Fluences per year at full Luminosity

![Graph showing fluences per year at full Luminosity for Pixel and SCT - barrel with different types of radiation: neutrons, pions, and other charged hadrons.]

LHC silicon detectors:

- All detectors have been extensively tested and developed for radiation tolerance and are expected to survive the LHC radiation environment.
- Some experiments have already foreseen upgrades (e.g. LHCb Velo after 3 years).

Super LHC

- Upgrade of LHC to 10 x higher Luminosity
  ⇒ 10 x higher radiation levels
  ⇒ Radiation damage will become a critical issue!
  ⇒ New, radiation tolerant detectors needed!

- Pixel detector: up to $\Phi_{eq} \approx 3.5 \times 10^{14}$ cm$^{-2}$/year
- Dominating type of particle is different for pixel (pions) and strip detectors (neutrons)

What is radiation damage?
- How to cope with it?

from M. Moll

Gregor Herten / 12. Radiation Damage of Silicon Detectors
12. Radiation Damage: Microscopic Defects

**Damage to the silicon crystal:** Displacement of lattice atoms

- Particle → $Si_S$
- $E_K > 25$ eV
- $E_K > 5$ keV

**Vacancy + Interstitial**

“point defects”, mobile in silicon, can react with impurities (O, C,..)

Point defects and clusters of defects

**Distribution of vacancies created by a 50 keV Si-ion in silicon (typical recoil energy for 1 MeV neutrons):**

- Schematic [Van Lint 1980]
- Simulation [M.Huhtinen 2001]

**Defects can be electrically active (levels in the band gap):**
- capture and release electrons and holes from conduction and valence band
- can be charged - can be generation/recombination centers - can be trapping centers

from M. Moll
14. CMS Detector

Key:
- Muon
- Electron
- Charged Hadron (e.g., Pion)
- Neutral Hadron (e.g., Neutron)
- Photon

Diagram showing the CMS detector components, including the silicon tracker, electromagnetic calorimeter, hadron calorimeter, superconducting solenoid, and iron return yoke interspersed with muon chambers.
14. CMS Silicon Tracker

Micro Strip:
- 214 m$^2$ of silicon strip sensors
- 11.4 million strips
- Diameter: 2.4 m

Pixel:
- Inner 3 layers: silicon pixels (≈ 1 m$^2$)
- 66 million pixels (100x150 µm$^2$)
- Precision: $\sigma(r\phi) \sim \sigma(z) \sim 15$ µm
Tracker performance: Clusters

Signal-to-Noise ratio (S/N) for clusters associated to tracks. The track direction is used to correct the signal for the path length with respect to normal incidence.

S/N value for TIB (320 um) and TOB (500 um): similar performance for thin and thick modules due to a different strip length: ~ 11 (~19) cm for TIB/TOB.

<table>
<thead>
<tr>
<th>Summary_ClusterStoNCorr_OnTrack_in_TIB</th>
<th>Summary_ClusterStoNCorr_OnTrack_in_TOB</th>
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<tr>
<td><strong>Entries</strong></td>
<td><strong>Entries</strong></td>
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<tr>
<td>22616</td>
<td>105616</td>
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<tr>
<td><strong>Mean</strong></td>
<td><strong>Mean</strong></td>
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<td><strong>RMS</strong></td>
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<tr>
<td>14.82</td>
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<td>$\chi^2$/ndf</td>
<td>$\chi^2$/ndf</td>
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<tr>
<td>20.23/15</td>
<td>158.4/19</td>
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<tr>
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<td><strong>Prob</strong></td>
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<tr>
<td>0.1633</td>
<td>0</td>
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<tr>
<td><strong>Width</strong></td>
<td><strong>Width</strong></td>
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<tr>
<td>1.927 ± 0.036</td>
<td>2.199 ± 0.018</td>
</tr>
<tr>
<td><strong>MP</strong></td>
<td><strong>MP</strong></td>
</tr>
<tr>
<td>25.38 ± 0.05</td>
<td>31.39 ± 0.02</td>
</tr>
<tr>
<td><strong>Area</strong></td>
<td><strong>Area</strong></td>
</tr>
<tr>
<td>8.978e+04 ± 635</td>
<td>4.093e+05 ± 1317</td>
</tr>
<tr>
<td><strong>GSigma</strong></td>
<td><strong>GSigma</strong></td>
</tr>
<tr>
<td>3.026 ± 0.104</td>
<td>3.49 ± 0.04</td>
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</table>

Most Probable Value (MPV) for each subsystem from the fit with a Landau function convoluted with a Gaussian. Value in agreement with expectation.

<table>
<thead>
<tr>
<th>S/N</th>
<th>TIB</th>
<th>TOB</th>
<th>TID</th>
<th>TEC</th>
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<td>25.4</td>
<td>31.4</td>
<td>27.5</td>
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</table>

12 March 2009 – TIPP09

L. Borrello – Results from the CMS SST Commissioning
Collision-like inside-outside reconstruction

Standard LHC tracking algorithm (CTF) inside-outside with some modifications:
- a wider seeding ($p_T > 5$ GeV, $|d0| < 10$ cm)
- correct accounting of energy losses for tracks in the upper half

For cosmic tracks in the central region ($p_T > 10$ GeV, $|d0| < 10$ cm, $|dz| < 30$ cm; $10 \leq \text{hits} \leq 25$), use one track and check another reconstructed track opposite to it

Results from cosmic data (in blue) are compared with MC events (in red)

High efficiency and good agreement between data and MC
The magnetic filed in the CMS TK (3.8 T) changes the drift direction of the holes respect to the depletion field by $\theta_L$.

$$ \Delta x = t \cdot \tan \theta_L $$

$$ \tan \theta_L = \mu_H \cdot B $$

Plot cluster size vs incident angle of the track on the module.

Minimum of the distribution $\rightarrow \theta_L$

$< \mu_H >$ (TIB, 320 $\mu$m sensors ) = 0.018 T$^{-1}$

$< \mu_H >$ (TOB, 500 $\mu$m sensors) = 0.023 T$^{-1}$

Different analyses techniques give compatible experimental results. Independent test from alignment confirms them.
Figure 1.1: Cut-away view of the ATLAS detector. The dimensions of the detector are 5 m in height and 44 m in length. The overall weight of the detector is approximately 7 tons. The ATLAS detector is nominally forward-backward symmetric with respect to the interaction point. The magnet configuration comprises a thin superconducting solenoid surrounding the inner detector cavity, and three large superconducting toroids (one barrel and two end-caps) arranged with an eight-fold azimuthal symmetry around the calorimeters. This fundamental choice has driven the design of the rest of the detector.

The inner detector is immersed in a 1 T solenoidal field. Pattern recognition, momentum and vertex measurements, and electron identification are achieved with a combination of discrete, high-resolution semiconductor pixel and strip detectors in the inner part of the tracking volume, and straw-tube tracking detectors with the capability to generate and detect transition radiation in its outer part.

High granularity liquid-argon (LAr) electromagnetic sampling calorimeters, with excellent performance in terms of energy and position resolution, cover the pseudorapidity range $|\eta| < 3$.

The hadronic calorimetry in the range $|\eta| < 1.7$ is provided by a scintillator-tile calorimeter, which is separated into a large barrel and two smaller extended barrel cylinders, one on either side of the central barrel. In the end-caps ($|\eta| > 1.57$), LAr technology is also used for the hadronic calorimeters, matching the outer $|\eta|$ limits of end-cap electromagnetic calorimeters. The LAr forward calorimeters provide both electromagnetic and hadronic energy measurements, and extend the pseudorapidity coverage to $|\eta| = 4.9$.

The calorimeter is surrounded by the muon spectrometer. The air-core toroid system, with a long barrel and two inserted end-cap magnets, generates strong bending power in a large volume within a light and open structure. Multiple-scattering effects are thereby minimised, and excellent muon momentum resolution is achieved with three layers of high precision tracking chambers.
Cut-away view of the ATLAS inner detector.
14. ATLAS Inner Detector

Silicon Strip Tracker (SCT)
- 6.3 million readout channels

**Barrel**
- 8 strip layers (4 space points) per track
- Stereo strips (40 mrad) parallel to \( z \)
- 6.4 cm long daisy chained sensors (80 µm pitch)
- Accuracies: 17 µm (R-ϕ), 580 µm (z)

**Endcap**
- Set of radial strips
- Set of stereo strips (40 mrad)
- Mean pitch about 80 µm
- Accuracies: 17 µm (R-ϕ), 580 µm (z)

Transition Radiation (TRT)
- 351,000 readout channels
- 36 hits per track
- 4 mm diameter straw tubes
- 144 cm long straws, divided in 2 halves
- Accuracy: 130 µm per straw
- Endcap: 37 cm long radial straws

Pixel Detector
- 3 pixel layers
- Pixel size in R-ϕ × z: 50 × 400 µm²
- Barrel accuracies: 10 µm (R-ϕ), 115 µm (z)
- Disk accuracies: 10 µm (R-ϕ), 115 µm (R)
- 80.4 million readout channels
Figure 4.2: Drawing showing the sensors and structural elements traversed by a charged track of $p_T = 10 \text{ GeV}$ at $\eta = 0.3$. The track traverses successively:

- beryllium beam pipe
- 3 pixel layers
- 4 double SCT layers
- about 36 TRT straws
Charged track of $p_T = 10$ GeV. It traverses
at $\eta = 1.4$: beryllium beam pipe, 3 pixel layers, 4 disks with double SCT layers, about 40 TRT straws.

at $\eta = 2.2$: beryllium beam pipe, 1 pixel B-layer, 2 endcap pixel disks, 4 disks with double SCT layers, no TRT straws.
Pixel module:
Top: Hybrid, MCC control chip, NTC thermistor, HV element, Type0 connector
Middle: Sensors
Bottom: FE board

Bottom left: bump bonding between sensor and FE board.
Bottom right: photo of pixel module
The transition radiator tracker consists of gas filled straws and polypropylene radiator foils.
**Figure 4.24:** A perspective cut-away view of the pixel detector. The view shows individual barrel and end-cap modules, supported with their associated services on staves and disks within an octagonal support frame.
Figure 4.28: The pixel detector during integration of the barrel, end-caps and their services: (a) the end-cap region; (b) the barrel detector region; (c) Patch Panel 1 (PP1) region; (d) Patch Panel 0 (PP0) region and (e) region of the optical transceivers on the service quarter-panels. See text for details.
Figure 4.33: Insertion of SCT barrel into the TRT barrel. The three module types of the TRT barrel are clearly identified. The SCT outer thermal enclosure is visible, together with the barrel services extending on support frames from each end.
14. ATLAS Cosmic Event
14. ATLAS ID: Event Displays
Figure 4.39: Distribution of average noise occupancy for all active module sides of the barrel and end-cap SCT (outer or middle end-cap modules on side C), as obtained at 1 fC threshold.

Figure 4.40: Distribution of the noise in electrons, normalised to a temperature of 0°C, for all active modules (or front-end chips) in the barrel and end-cap SCT (side C).
**Figure 4.46:** Material distribution \((X_0, \lambda)\) at the exit of the ID envelope, including the services and thermal enclosures. The distribution is shown as a function of \(|\eta|\) and averaged over \(\phi\). The breakdown shows the contributions of different ID components, independent of the sub-detector.
Residual distribution in x, integrated over all hits-on-tracks in the pixel barrel for the nominal geometry and the preliminary aligned geometry.

The residual is defined as the measured hit position minus the expected hit position from the track extrapolation. Shown is the projection onto the local x coordinate, which is the precision coordinate.

Tracks are selected to have $p_T > 2$ GeV, $|d_0| < 50$ mm, $|z_0| < 400$ mm (in other words they are required to go through the pixel L0).
Cosmic tracks crossing the entire ID leave hits in both the upper and lower halves of the ID.

These tracks can be split near the interaction point and fit separately, resulting in two collision-like tracks that can then be compared.

The plots show the difference in the $d_0$ track parameter between the two split tracks. Tracks are selected to have $p_T > 2$ GeV, $|d_0|<50$mm, $|z_0|<400$mm (in other words they are required to go through the pixel L0).

Tracks also are required to have a hit in the Pixel B layer, 3 Pixel hits and in total 7 Silicon hits.
Further Reading

General books about particle detectors:

W. R. Leo - Techniques for Nuclear and particle Physics Experiments

K. Kleinknecht - Detectors for Particle Radiation

C. Grupen - Particle Detectors

G. Lutz - Semiconductor Radiation Detectors

W. Blum, W. Riegler, G. Rolandi - Particle Detection with Drift Chambers

Online:
http://physics.web.cern.ch/Physics/ParticleDetector/BriefBook/