Charged Particle Tracking in High Energy Physics

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High Energy Collider Detectors

• **Tracking Detectors (or Trackers) = momentum measurement**
  - closest to interaction point: **vertex detectors** (mainly silicon pixel detectors)
    - measure the **primary interaction vertex** and **secondary vertices** from decay particles
  - main or central tracking detectors
    - measure the **momentum** by curvature in magnetic field
    - two main technologies: silicon detectors (e.g. strip sensors) and gaseous detectors (e.g. TPC, TRT)

• **Calorimeters = energy measurement**
  - electro-magnetic calorimeters
    - measure **energy of light EM particles** (electrons, positrons, photons) based on electro-magnetic showers by bremsstrahlung and pair production
    - two concepts: homogeneous (e.g. CMS) and sampling (e.g. ATLAS) calorimeters
  - hadron calorimeters
    - measure **energy of heavy (hadronic) particles** (pions, kaons, protons, neutrons) based on nuclear showers created by nuclear interactions

• **Muon Detectors = momentum measurement for muons**
  - outermost detector layer, basically a tracking detector
3 major technologies are used for tracking detectors:

- **Gaseous detectors**
  - Ionization in gas (creation of electron – ion pairs)
    - typically ~100 electrons/cm
    - not sufficient to create significant signal height above noise for standard amplifiers
  - **Gas amplification needed**
    - gas amplification ~$10^4$ to reach sufficient signal height over noise

- **Silicon detectors**
  - Ionization (creation of electron – hole pairs) in solid state material
    - typically ~100 electron-hole pairs/μm
  - **No amplification needed**
    - signal height in a ~300 μm thick detector high enough
    - no impact ionization (like used e.g. in avalanche photodetectors) needed

- **Fiber trackers**
  - Scintillating fibers
    - scintillating light detected with photon detectors (sensitive to single electrons)
Gaseous Detectors – Ionization of Gases

- Primary number of ionizations per unit length is Poisson-distributed
  - typically ~30 primary electrons/cm in gas at 1 atm

- However, primary electrons sometimes receive large energies
  - can ionize other atoms (secondary ionization, production of ionization clusters)
  - can even create secondary visible track (“delta electrons”)
  - large fluctuations of energy loss by ionization
  - typically: total ionization = 3 x primary ionization
    - on average ~ 90 electrons/cm in gas
Energy Loss Distribution in detectors

- Real detectors cannot measure \( \langle dE/dx \rangle \)
  - The energy \( \Delta E \) deposited in a layer of finite thickness \( \delta x \) is measured.

- For thin layers of solids or low density materials:
  - Few collisions, some with high energy transfer.
  - Energy loss distributions show large fluctuations towards high losses; Landau distribution with tails

**Example**: Si sensor: 300 \( \mu \)m thick. \( \Delta E_{\text{most probable}} \approx 82 \text{ keV} \) \( \langle \Delta E \rangle \approx 115 \text{ keV} \)

- For thick layers and high density materials:
  - Many collisions
  - Central Limit Theorem \( \Rightarrow \) Gaussian shaped distributions
Elastic Scattering

• Most basic interaction of a charged particle in matter
  – elastic scattering with a nucleus
    = Rutherford (Coulomb) scattering
  – An incoming particle with charge $z$ interacts elastically with a target of nuclear charge $Z$.

  Cross section for this e.m. process is given by the Rutherford formula:

  \[
  \frac{d\sigma}{d\Omega} = 4zZe^2 \left( \frac{m_ec}{\beta p} \right)^2 \frac{1}{\sin^4 \theta/2}
  \]

• Approximations
  – non-relativistic
  – no spins

• Scattering angle and energy transfer to nucleus usually small
  – No (significant) energy loss of the incoming particle
  – Just change of particle direction


Ernest Rutherford
May 1911
Multiple Scattering

- In a sufficiently thick material layer a particle will undergo multiple scattering
  - after passing material layer of thickness \( L \) particle leaves with some displacement \( r_{\text{plane}} \) and some deflection angle \( \theta_{\text{plane}} \)

\[ \theta_{\text{plane}} \approx \frac{1}{\sqrt{X_0 P}} \sqrt{\frac{L}{X_0}} \]

\( \Theta_0 \) = width of distribution

- Multiple scattering dominates the momentum measurement resolution for low momenta (see later)
  - \( X_0 \) = radiation length (see later)
Momentum Measurement

- Moving charged particles are deflected by magnetic fields
  - In a homogeneous \( B \) field particle follows circle with radius \( r \)

\[
p_t[\text{GeV}/c] = 0.3 \cdot B[T] \cdot r[\text{m}]
\]

- \( p_t \) is the component of the momentum orthogonal to \( B \) field

\( p_t : \text{transverse momentum} \)

- no particle deflection parallel to magnetic field
- if particle has \textit{longitudinal momentum} component, the particle will follow a helix

\[
p = q \cdot B \cdot r
\]

measurement of \( p_t \) via measuring the radius

total momentum \( p \) to be measured via dip angle \( \lambda \)

\[
p = \frac{p_t}{\sin \lambda}
\]
Momentum measurement – Relative Error

• How to measure the radius \( r \) (curvature) ?
  – Tracking Detectors measure the positions of the track along various points along the track (circle)

\[
\rho = \frac{L^2}{8s} + \frac{s}{2} \quad \text{if } s << L \quad r \approx \frac{L^2}{8s}
\]

sagitta \( s \) / radius \( r \) is obtained by a circle fit through measurement points along the track with point resolution \( \sigma_{r\phi} \) for each point

\[
\sigma_S = \sqrt{\frac{A_N}{N+4}} \cdot \frac{\sigma_{r\phi}}{8} \quad \text{with statistical factor } A_N = 720
\]

R.L. Gluckstern, NIM 24 (1963), 381

relative transverse momentum resolution \( \sigma_{p_T}/p_T \)

• degrades linearly with momentum
• improves linearly with B field
• improves quadratically with radial extension of detector

\[
\sigma_{p_T} = \frac{8p_T}{0.3BL^2} \cdot \sigma_S
\]

\[
\frac{\sigma_{p_T}}{p_T} \propto p_T
\]
• The (transverse) momentum resolution is dominated by two contributions
  
  – contribution from measurement error
    \[ \frac{\sigma_{p_T}}{p_T} \propto p_T \]
  
  – contribution from multiple scattering
    (remember)
    \[ \theta_0 \propto \frac{1}{p_T} \sqrt{\frac{L}{X_0}} \quad \sigma_{r\phi} |_{MS} \propto \theta_0 \]
    \[ \frac{\sigma_{p_T}}{p_T} \propto p_T \cdot \sigma_{r\phi} \]

  More precise:
  \[ \frac{\sigma(p_T)}{p_T} |_{MS} = 0.045 \frac{1}{B \sqrt{LX_0}} \]

  Example: Detector (L=1m) filled with 1atm Argon gas (X_0=110m); B=1T
  \[ \frac{\sigma(p_T)}{p_T} |_{MS} = 0.5\% \]
Vertex Detectors

Besides momentum measurement tracking detectors have to measure:

• Primary and Secondary Decay Vertices
  – Example: B lifetime $\tau_B \sim 1.6 \text{ ps} \Rightarrow \gamma c \tau_B = \gamma \cdot 500 \text{ m} \mu$ with $\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$
  – Figure of merit: Impact parameter resolution
  – Physics example from LHCb (2010): $B^+ \rightarrow J/\Psi K^+$

[Image: Diagram showing primary and secondary vertices with impact parameter resolution and decay lifetime.]
Impact parameter resolution

- Uncertainty on the transverse impact parameter, $d_0$, depends on the detector radii and space point precisions.

- Simplified formula for just two layers:

\[
\sigma_{d_0}^2 = \frac{r_2^2 \sigma_1^2 + r_1^2 \sigma_2^2}{\left(r_2^2 - r_1^2\right)^2} + \sigma_{MS}^2
\]

  - Suggests small $r_1$, large $r_2$, small $\sigma_1$, $\sigma_2$

  - But precision is degraded by multiple scattering….

Example: LHCb (VELO)

\[
\sigma_{IP} = \left(10 + 29/p_T[GeV/c]\right) \mu m
\]

[PoS VERTEX2010:014,2010.]
Gaseous Detectors – Geiger-Müller Tube

• The Geiger-Müller tube (1928 by Hans Geiger and Walther Müller)
  – Tube filled with inert gas (He, Ne, Ar) + organic vapour
  – Central thin wire (20 – 50 µm ∅), high voltage (several 100V) between wire and tube

  • Strong increase of E-field close to the wire
    • Electrons gain more and more energy
    • above some threshold (>10 kV/cm)
    • electron energy high enough to ionize other gas molecules
    • newly created electrons also start ionizing

  • avalanche effect: exponential increase of electrons (and ions)

  • measurable signal on wire
    • organic substances responsible for “quenching” (stopping) the discharge
• Signal formation depending on electron and ion drift
  - Signal on cathode and anode is induced by the moving electrons and ions
  - Electrons from the avalanche are produced very close to the wire and collected in a very short time (t < ns)
  ⇒ Small contribution of electrons to signal

\[ dv = \frac{Q}{lCV_0} \cdot \frac{d\varphi(r)}{dr} \cdot dr \]

- Length of cylinder \( l \)
- Capacitance \( C \)
- Voltage applied \( V_0 \)
- Moving charge \( Q \)

• Main part of signal produced by ions
  - Ions drift back to cathode over long distance (several mm or cm) and time (many \( \mu s \) or even ms)

<table>
<thead>
<tr>
<th>t (ns)</th>
<th>Signal after electronics shaping (RC high-pass filter with different time constants)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>pure signal (no electronics shaping) from ions drifting away from anode wire</td>
</tr>
<tr>
<td>100</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td></td>
</tr>
</tbody>
</table>

| t (ns) | Pure signal from ions drifting away from anode wire
|-------|----------------------------------------------------------------------------------|
• MWPC – Multi Wire Proportional Chamber
  – Simple idea: Multiply the SWPC (Nobel Prize by Charpak in 1992)
  – Usually binary read out
    ⇒ Resolution limited to \( d = \text{distance between wires} \):
    \[
    \sigma_x \approx \frac{d}{\sqrt{12}}
    \]
    for \( d = 1 \text{ mm} \) \( \sigma_x = 300 \mu m \)

• Drift Chamber
  – Obtain position from drift time of electrons
    ⇒ Advantage: requires less wires, less channels
    ⇒ needs external source for start signal
      (scintillator or beam crossing signal)
    ⇒ need to know drift velocity \( v_D \) to calculate
distance \( s \) to wire
    \[
    s = \int_{t_{\text{start}}}^{t_{\text{stop}}} v_D \, dt
    \]
TPC – Time Projection Chamber

• Full 3D track reconstruction
  – x-y from wires and segmented cathode of MWPC (or GEM)
  – z from drift time

• Momentum resolution
  – Space resolution + B-Field

• Energy resolution
  – Measure of primary ionization

• Positive Ion backflow
  – Needs a gating plane to stop ions from backdrift into chamber
• Alice TPC
  – HV central electrode at –100 kV
  – Drift length: 250 cm at E=400 V/cm
  – Gas: Ne-CO₂ 90-10
  – Space point resolution ~500 μm
  – dp/p = 2%@1GeV; dp/p = 10%@10GeV

• Alice: Heavy Ion Event Display

08.Nov.2010
Pb+Pb
\sqrt{s} = 2.76 ATeV
\sqrt{s} = 575 TeV/ion
RPC - Resistive Plate Chambers

- RPC - No wires! - Resistive plates from Bakelite ($\rho=10^{10}-10^{12}\,\Omega\text{cm}$) or window glass ($\rho=10^{12}-10^{13}\,\Omega\text{cm}$) in front of metal electrodes
  - gas gap: 0.25 – 2 mm; electric fields: 50-100 KV/cm
  - time resolution: 50ps (100 KV/cm), 1ns (50KV/cm)
  - Application: Trigger Detectors, Time of Flight (TOF)
  - Resistivity limits rate capability ($\text{kHz/cm}^2$ for $10^{10}\,\Omega\text{cm}$)
    - Time to remove avalanche charge from the surface of the resistive plate is in ms to s range.

- MRPC – Multi gap RPC
  - higher efficiency
  - exceptional time resolution

![Diagram of RPC and MRPC](image)
Micro Strip Gas Chambers - MSGCs

- Gain is not provided by wires but by metal strips on resistive electrodes.
- Due to small pitch and fast ion collection MSGCs have very high rate capability.

1990s: Candidates for inner tracking system of ATLAS and CMS
- Unfortunately MSGCs are rather prone to discharge, particularly in hostile environments.
MPGDs - Micro Pattern Gas Detectors

- **MICROMEGA** Micro Mesh Gas detector
  
  **Drift electrode (–HV)**

  micromesh

  readout electrode

  – \( E_a/E_i \sim 50 \): - secure electron transparency
    - positive ion flowback suppression.

- **GEM** Gas Electron Multiplier

  thin metal-coated polymer foils with holes

  \( \varnothing \) 50-70 µm

... being implemented now in HEP experiments
... many ongoing developments (see CERN RD51)
**Solid State Detectors – Why Silicon?**

- **Some characteristics of Silicon crystals**
  - Small band gap \( E_g = 1.12 \text{ eV} \Rightarrow E(\text{e-h pair}) = 3.6 \text{ eV} (~ 30 \text{ eV for gas detectors}) \)
  - High specific density \( 2.33 \text{ g/cm}^3 \); \( \text{dE/dx (M.I.P.)} \approx 3.8 \text{ MeV/cm} \approx 106 \text{ e-h}/\mu\text{m (average)} \)
  - High carrier mobility \( \mu_e = 1450 \text{ cm}^2/\text{Vs}, \mu_h = 450 \text{ cm}^2/\text{Vs} \Rightarrow \text{fast charge collection (<10 ns)} \)
  - Very pure \(< 1\text{ ppm impurities and } < 0.1\text{ ppb electrical active impurities}\)
  - Rigidity of silicon allows thin self supporting structures
  - Detector production by microelectronic techniques
    \( \Rightarrow \) well known industrial technology, relatively low price, small structures easily possible

- **Alternative semiconductors**
  - Diamond
  - Gallium arsenide (GaAs)
  - Silicon Carbide (SiC)
  - Germanium (Ge)

<table>
<thead>
<tr>
<th></th>
<th>Diamond</th>
<th>SiC (4H)</th>
<th>GaAs</th>
<th>Si</th>
<th>Ge</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Atomic number Z</strong></td>
<td>6</td>
<td>14/6</td>
<td>31/33</td>
<td>14</td>
<td>32</td>
</tr>
<tr>
<td><strong>Bandgap ( E_g \text{ [eV]} )</strong></td>
<td>5.5</td>
<td>3.3</td>
<td>1.42</td>
<td>1.12</td>
<td>0.66</td>
</tr>
<tr>
<td><strong>E(e-h pair) [eV]</strong></td>
<td>13</td>
<td>7.6-8.4</td>
<td>4.3</td>
<td>3.6</td>
<td>2.9</td>
</tr>
<tr>
<td><strong>Density [g/cm³]</strong></td>
<td>3.515</td>
<td>3.22</td>
<td>5.32</td>
<td>2.33</td>
<td>5.32</td>
</tr>
<tr>
<td><strong>Electron mobility ( \mu_e \text{ [cm}^2/\text{Vs]} )</strong></td>
<td>1800</td>
<td>800</td>
<td>8500</td>
<td>1450</td>
<td>3900</td>
</tr>
<tr>
<td><strong>Hole mobility ( \mu_h \text{ [cm}^2/\text{Vs]} )</strong></td>
<td>1200</td>
<td>115</td>
<td>400</td>
<td>450</td>
<td>1900</td>
</tr>
</tbody>
</table>
How to obtain the signal?

In a pure intrinsic (undoped) semiconductor the electron density $n$ and hole density $p$ are equal.

$$n = p = n_i$$  
For Silicon: $n_i \approx 1.45 \cdot 10^{10} \text{ cm}^{-3}$

4.5 $\cdot$ 10$^8$ free charge carriers in this volume, but only 3.2 $\cdot$ 10$^4$ e-h pairs produced by a M.I.P.

$\Rightarrow$ Reduce number of free charge carriers, i.e. deplete the detector

$\Rightarrow$ Most detectors make use of reverse biased p-n junctions
Doping, resistivity and p-n junction

- **Doping: n-type silicon**
  - add elements from V\textsuperscript{th} group
  - donors (P, As,..)
  - electrons are majority carriers

- **Doping: p-type silicon**
  - add elements from III\textsuperscript{rd} group
  - acceptors (B,..)
  - holes are majority carriers

- **resistivity** $\rho$
  - carrier concentration $n$, $p$
  - carrier mobility $\mu_n$, $\mu_p$
  \[ \rho = \frac{1}{q_0 (\mu_n n + \mu_p p)} \]

- **p-n junction**
  - There must be a single Fermi level!
  - band structure deformation
  - potential difference
  - depleted zone

- detector grade | electronics grade
  | doping | $\approx 10^{12}$ cm\(^{-3}\) | $\approx 10^{17}$ cm\(^{-3}\)
  | resistivity $\rho$ | $\approx 5$ k\(\Omega\)·cm | $\approx 1$ \(\Omega\)·cm
Reverse biased p-n junction

Poisson’s equation
\[- \frac{d^2}{dx^2} \phi(x) = \frac{q_0}{\varepsilon \varepsilon_0} \cdot N_{\text{eff}}\]

Positive space charge, \(N_{\text{eff}} = |P|\) (ionized Phosphorus atoms)

Neutral bulk (no electric field)

- Depleted zone growth with increasing voltage \((W \propto \sqrt{V_B})\)
  - \(+V_B < V_{\text{dep}}\)
  - \(+V_B > V_{\text{dep}}\)

- Full charge collection only for fully depleted detector \((V_B > V_{\text{dep}})\)

Electrical charge density

Electrical field strength

Electron potential energy

Depletion voltage \(V_{\text{dep}}\) = \(\frac{q_0}{\varepsilon \varepsilon_0} \cdot |N_{\text{eff}}| \cdot d^2\)

detector thickness \(d\)

effective space charge density \(N_{\text{eff}}\)
Single Sided Strip Detector

- Segmentation of the $p^+$ layer into strips (Diode Strip Detector) and connection of strips to individual read-out channels gives spatial information

- Resolution $\sigma$ depends on the pitch $p$ (distance from strip to strip)

  - e.g. detection of charge in binary way (threshold discrimination)
  - and using center of strip as measured coordinate results in $\sigma = \frac{p}{\sqrt{12}}$

  typical pitch values are 20 $\mu$m– 150 $\mu$m  $\Rightarrow$ 50 $\mu$m pitch results in 14.4 $\mu$m resolution

- using n-type silicon with a resistivity of $\rho = 2$ K$\Omega$cm ($N_D \sim 2.2 \times 10^{12}$cm$^{-3}$)
  - results in a depletion voltage $\sim 150$ V

- typical thickness: 300 $\mu$m (150 $\mu$m - 500 $\mu$m used)
Signal to noise ratio

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

**Noise sources:** (ENC = Equivalent Noise Charge)
- Capacitance \( ENC \propto C_d \)
- Leakage Current \( ENC \propto \sqrt{I} \)
- Thermal Noise (bias resistor) \( ENC \propto \sqrt{\frac{k_B T}{R}} \)

- Good hits selected by requiring \( N_{ADC} > \) 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 \( S/N \)!
Detector Module

- **Detector Modules** “Basic building block of silicon based tracking detectors”
  - Silicon Sensors
  - Mechanical support (cooling)
  - Front end electronics and signal routing (connectivity)

- **Example: ATLAS SCT Barrel Module**

**Silicon sensors (x4)**
- 64 x 64 mm²
- p-in-n, single sided
- AC-coupled
- 768 strips
- 80 μm pitch/12 μm width

**Mechanical support**
- TPG baseboard
- BeO facings

**Hybrid (x1)**
- flexible 4 layer copper/kapton hybrid
- mounted directly over two of the four silicon sensors
- carrying front end electronics, pitch adapter, signal routing, connector

- **ASICS (x12)**
  - ABCD chip (binary readout)
  - DMILL technology
  - 128 channels

- **Wire bonds (~3500)**
  - 25 μm Al wires

- **ATLAS – SCT**
  - 15.552 microstrip sensors
  - 2.112 barrel modules
  - 1.976 forward modules
  - 61 m² silicon, 6.3·10⁶ strips

\[\sigma(r\phi) \sim 16 \, \mu m, \ \sigma(z) \sim 850 \, \mu m \ [\text{NIMA538 (2005) 384}]\]
**Pixel Detectors**

- **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 are used in all LHC experiments: ATLAS, ALICE, CMS and LHCb

**Solder Bump: Pb-Sn**

**Flip-chip technique**
Example: The CMS Silicon Tracker

- **CMS**
  - **Inner Tracker**
    - Inner Barrel (TIB – 4 layer)
    - Outer Barrel (TOB 6-layer)
    - Inner Disks (TID)
  - End Cap (TEC)

- **CMS – Compact Muon Solenoid**
  - **Micro Strip:**
    - ~ 214 m² of silicon strip sensors
    - 11.4 million strips
  - **Pixel:**
    - Inner 3 layers: silicon pixels (~ 1m²)
    - 66 million pixels (100x150μm)
    - Precision: σ(rφ) ~ σ(z) ~ 15μm
    - Most challenging operating environments (LHC)
• Silicon Detectors have a very good point resolution ~10 µm
  – but where is the point exactly in space w.r.t. the global detector coordinate system?
  – resolution is not absolute accuracy

• Point is usually defined by strip number or pixel number
  – i.e. within the local Si detector frame (10 x 10 cm² scale)
  – Limited mechanical positioning of one Si detector element to each other
    • Shift and rotation of the elements, bowing (non flatness) etc.
    • Need to know all positions of the detector elements

• Possible alignment strategies
  – Can measure positions in the lab before installation (survey)
    • Stability after installation?
    • Use alignment system (e.g. laser tracks, piezo) to measure positions
    • Align with LHC tracks, e.g. minimize deviations from track in χ² fit
Material Budget

- Tracking Detectors should be light-weighted and thin
  - multiple scattering by material degrades resolution at low momenta
  - unwanted photon conversions in front of calorimeters
  - material often very inhomogeneous (in particular Si detectors)

- Power & cooling adds most of the material
  - not the Si sensor material
### Ongoing R&D activities *(LHC upgrade)*

**Tracking Detector Developments ongoing for several projects**

**Example:** LHC upgrade (High Luminosity LHC):

* Larger Occupancy and Higher Radiation levels

- **Need higher granularities at larger radius**
  - Pixel detectors reaching out further in radius and coming closer to beam
  - Silicon Strip Sensors with shorter strips
  - New trigger concepts using silicon detectors

- **Need radiation tolerant detectors**
  - R&D on sensor materials (Defect Engineered Silicon, Diamond, ..)
  - R&D on sensor concepts (n-in-p sensors, 3D sensors, ..)

- **Exploit industrial developments**
  - ‘3D integration’ (Combine sensor and electronics)

- **Many other issues**
  - Powering, cooling, reduction of power consumption, cost, mass reduction, ..
**Summary**

*Tracking: Particle Track Reconstruction*

- **Vertexing**
  - distinguish primary vertices
  - measure impact parameter and secondary vertices, lifetime tagging

- **Momentum Measurement** (from curvature of track in magnetic field)
  - Momentum resolution has two main contributions
    - Error from multiple scattering, independent of momentum, dominates at low momentum, requires thin/light detectors
    - Error from point measurements, dominates at high momenta, large track length and strong B-Field helps: \( \propto 1/(BL^2) \), need big detectors and strong B-Field to measure high momenta

- **Tracking Performance**
  - Material budget (Trade off between precision and material!)
  - Alignment (Improve quality of tracks)

- **Tracking Detectors (Choice of Technology)**
  Mainly two (three) types of track detectors
  - Silicon detectors since early 1990s, very good point resolution, many electronics channels, “thick” compared to wire chambers
  - Gaseous detectors (with wires) since 1960s, point resolution limited to ~50-150 µm
  - Fiber trackers with scintillating fibers + photon detectors

- **Intensive tracking detector R&D ongoing for LHC upgrade, LC, CLIC, ....**
Acknowledgements and Literature

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  – Michael Hauschild, CERN, Tracking Detectors (ESI 2009)
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    Particle Detectors (CERN Summer Student Lectures 2003)
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  – Gregor Herten, Uni Freiburg, Particle Detection: Trackers (HCP School 2009)
  – Pippa Wells, CERN, Tracking at the LHC (EDIT 2011 School)

• Literature – Further Reading
  – C.Grupen and B.Shwartz, Particle Detectors, Cambridge University Press
  – G.Lutz, Semiconductor Radiation Detectors, Springer
  – H.Spieler, Semiconductor Detector Systems, Oxford University Press
  – G.Knoll, Radiation Detection and Measurement, John Wiley and Sons
  – M.Sze, Physics of Semiconductor Devices, Wiley-Interscience
  – L.Rossi, Pixel Detectors, Springer
  – F.Hartmann, Evolution of Silicon Sensor Technology in Particle Physics, Springer