INSTRUMENTATION AT THE LHC

A CLOSER LOOK TO THE SILICON DETECTOR SYSTEMS

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The 8th International “Hiroshima” Symposium on the Development and Application of Semiconductor Tracking Detectors at Academia Sinica, Taipei, December 5-8, 2011
In mid/late 1980 the project of a high luminosity (>10^{34} \text{cm}^{-2}\text{s}^{-1}) hadron collider ($\sqrt{s}=16$ TeV) at CERN took shape. LHC was planned as a competitor to the SSC (40 TeV and $10^{33} \text{cm}^{-2}\text{s}^{-1}$) in the US (but earlier!!!).

Detector concepts for the high luminosity LHC:
- Focus on calorimetry and muon detection
- Widespread believe that vertexing and full tracking not possible at these luminosities.

Typical detector proposals:
- Magnetic Iron „μball“ + Calorimeters + TRD
- Beam dump type muon spectrometer
Detector Concepts* (1988)

Beam Dump type Experiment:

* for the LHC high luminosity option
However, in the same conference (Como 1988) some foresighted colleagues proposed already large tracker based on silicon microstrips for SSC and LHC experiments:


40 m² of silicon, $\sigma_{pt}/p_t=8\%$ at 1 TeV
Late 1980 till 2011

Huge development in the field of silicon detectors, electronics, connectivity, mechanics, cooling, etc.

- LEP Experiments first application in collider experiment 1989 - 2000
- CDF and DO first application at a hadron collider (1985*) – 1992 - 2011

* no silicon detectors initially

Silicon detectors became indispensable, they opened new fields of research (e.g. heavy flavour physics) and the size became larger and larger!

Plot stolen from presentation of D. Christian at TIPP 2011
(who has stolen from someone he can’t remember whom)
But also number of physicists and institutes involved in silicon tracking systems grew:

**1980 to 2011**

NA1 **one institute** (CERN), 8 physicists
NA11 **3 institutes** (CERN, TU Munich, MPI Munich)

ALEPH, DELPHI, L3, OPAL
~ **55 institutes** (1st Si detectors, number increased for upgrades)

ALICE, ATLAS, CMS, LHCb
~ **165 institutes** involved
Experiments at the LHC
ATLAS Inner tracking system:
3 Si pixel layers, 3 discs - Pixel
4 Si strip layers, 9 discs - SCT
Transition Radiaton Tracker - TRT
(straw tubes emmbeded in fibre radiator)
Larges Pixel detector at LHC!
3 barrel layers: 1456 modules
3 disks per end-cap: 288 modules
80M readout channels
Innermost layer at radius 50.5 mm
Evaporative $C_3F_8$ cooling

96.8% of the detector active in data taking
(The percentage of disabled modules only 2.1% up to 3.2% in 3 years of operations)

Readout chip measures pulse height by Time-over-Threshold
→ used for $dE/dx$ measurement.
4 Barrel layers: 2112 modules
2x9 endcap disks: 1976 modules
Coverage: 30 cm < r < 52 cm, |η|<2.5
Active material: 61 m² silicon
Readout: 6.3 million channels, Binary readout
C₃F₈ cooling: -7° C ... +4.5° C

Modules: 2 single sided sensors glued back to back

Less than 0.2% disabled noisy strips.
0.75% modules out of readout (cooling, TX failures, etc.)
Excellent performance of ATLAS Pixel and Strip Detector

**E.g. Pixel resolution (rΦ):**

Pixel Hit to track association efficiency ~99%

![Graph showing Pixel resolution](image)

B. Di Girolamo, Vertex2011

Width close to MC of a perfectly aligned detector.

**E.g. SCT Hit efficiency barrel:**

![Graph showing SCT Hit efficiency](image)

More details in talks by Cecile Lapoire (Pixel) and Dave Robinson (SCT).
ALICE a dedicated heavy ion experiment
Lower luminosity $10^{27}$ cm$^{-2}$s$^{-1}$ during Pb-Pb collisions,
but charged particle multiplicities of up to 8000 per unit of rapidity.

ALICE Inner Tracking System:
Largest TPC in the world:
5 m length, radius from 0.85 – 2.5 m, 88 m$^3$ gas volume
+ silicon system inside
3 different silicon detector technologies:
- Hybrid Silicon Pixel Detector (SPD)
- Silicon Drift Detector (SDD)
- Double Sided Strip Detector (SSD)

Operation 2010/11 not without problems:
- SPD: 1.8% low eff. or dead channels, cooling problems effecting ~30% of modules
- SDD: 1.5% dead + 0.7% noisy channels, 6% modules out of acquisition
- SSD: 1.5% dead or noisy channels, 8% modules out of acquisition

R. Santoro, Vertex2011
Challenging calibration: interplay between alignment, drift velocity and time-zero calibration.

Alignment, before and after drift velocity correction:

Residual misalignment ≈35µm in the drift direction
4 out of 6 silicon layers with analogue information (SDD and SSD)

Results for particle identification in p-p and Pb-Pb data
   ITS standalone tracks
   Hadron separation below 100 MeV/c ← **Low momentum cutoff of 100 MeV**
   Good pions / kaons separation up to 0.5 GeV/c
   Good pions and protons separation up to 1 GeV/c
D meson reconstruction in PbPb

Pb – Pb collisions (2010)
2.76 TeV/nucleon (≈ 30 M events MB)

Prove of the ITS performance:
Find charm decays in Pb-Pb collisions (crucial is the ITS impact parameter resolution).

e.g. D0:

More details in talk by Vito Manzari.
LHCb experiment dedicated to heavy flavour physics

- HCAL
- ECAL
- RICH2
- Outer Tracker straw Tubes
- Magnet
- TT Si
- VELO&PU Si
- Muon MWPCGEM
- Inner Tracker Si
- Inner Tracker see talk by Greig Cowan.
During stable beams closest silicon 7 mm from the beam.
21 modules per half (r and Φ sensor per module)
n-n sensors (300 µm, pitch 40 µm – 100 µm)
Operated in secondary vacuum (separated from LHC vacuum by 300 µm foil)

Evaporative CO$_2$ cooling at -30 C
→ no problems during operation.

Quasi circular sensors with inner opening:
Alignment and impact parameter resolution

Stability of two half alignment ±5 µm/ ±2 µm in x/y
Method: reconstruct primary vertex with the two halves

Impact parameter resolution for high $p_t$ tracks 13 µm.

MC predicts 11 µm
Discrepancy is under investigation (summer 2011)
Possible reasons are material description, alignment effects.
Time resolution important, e.g. to measure $B_s^0 - \bar{B_s}^0$ mixing frequency.

Time resolution obtained from prompt $J/\psi = 50$ fs!

More details in talk by Paula Collins.
First experiment with full Silicon tracker system.

Largest Silicon Detector ever built.

+ Silicon strip sensors inside the preshower detector
Talk by Chia-Ming Kuo and poster by Kai-Yi Kao.
Pixel detector:
- 1 m² detector area
- 1440 pixel modules
- 66 million pixels

Strip detector:
- ~200 m² of silicon sensors
- 24,244 single silicon sensors
- 15,148 modules
- 9,600,000 strips
  ≈ electronics channels
- 75,000 read out chips (APV25)
- 25,000,000 Wire bonds
15148 modules in 27 mechanically different geometries – real mass production.

Examples for end cap geometries:

Single sided sensors:
- $p^+$ on $n$
- thickness 320 µm and 500 µm
- two different wafer resistivities

Stereo modules with sensors back to back.

Cooling $C_6F_{14}$ at present set to 4ºC. Some problems with leak rate (5 out of 90 cooling loops shut down)

**Status: 2.2% dead channels**
Pixel is inserted on rails.
→ can be extracted for maintenance (done winter 2010)

Pixel status: 96.9% functional ROCs (15324 from a total of 15840)

Frequent firmware updates necessary.
Knowledge of material distribution of the tracker is crucial for physics analysis. Use counting of photon conversions and nuclear interactions to probe material.
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Good agreement within 10%!
Resolution on transverse momentum measured using J/ψ mass line-shape. Tracks from J/ψ have on average a momentum of a few GeV. At this momenta the inner tracker dominates the momentum measurement.

Sensitive to:
- Knowledge of the tracker material
- Alignment
- B field
- Reconstruction algorithms

In general good agreement with MC (~5%, some deviation in the transition region of barrel to end cap).

More results in talk by Francesco Palmonari.
Tracking at High Pile Up

Event with 20 vertices:

~ 10 cm

And all vertices nicely reconstructed........
TOTEM

Last but not least.........TOTEM

TOTEM is dedicated to the measurement of the total cross section, elastic scattering and diffraction dissociation at the LHC.

Cathode strip chambers at 10.5 m, Triple GEMs at 14 m AND silicon sensors in Roman Pots at 147 m and 220 m from the interaction point (IP5 CMS).
TOTEM Edgeless Sensors

240 edgeless sensors
12,288 readout channels
Active strips only 50 µm from edge

Closest approach of the system foreseen: 10σ of the beam.
### Summary

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Detector</th>
<th>Silicon Area $m^2$</th>
<th>Nr. of channels Millions</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>SCT</td>
<td>61</td>
<td>6,27</td>
</tr>
<tr>
<td></td>
<td>Pixel</td>
<td>2,2</td>
<td>80</td>
</tr>
<tr>
<td>ALICE</td>
<td>SPD</td>
<td>0,21</td>
<td>9,8</td>
</tr>
<tr>
<td></td>
<td>SDD</td>
<td>1,31</td>
<td>0,133</td>
</tr>
<tr>
<td></td>
<td>SSD</td>
<td>5</td>
<td>2,6</td>
</tr>
<tr>
<td>LHCb</td>
<td>VELO</td>
<td>0,0055</td>
<td>0,172</td>
</tr>
<tr>
<td></td>
<td>TT</td>
<td>8,2</td>
<td>0,143</td>
</tr>
<tr>
<td></td>
<td>IT</td>
<td>4,2</td>
<td>0,129</td>
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<tr>
<td>CMS</td>
<td>Pixel</td>
<td>1</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td>SST</td>
<td>200</td>
<td>9,6</td>
</tr>
<tr>
<td></td>
<td>Preshower</td>
<td>16</td>
<td>0,137</td>
</tr>
<tr>
<td>TOTEM</td>
<td></td>
<td>0,294</td>
<td>0,123</td>
</tr>
<tr>
<td><strong>LHC total</strong></td>
<td></td>
<td><strong>300 m²</strong></td>
<td><strong>175 Million</strong></td>
</tr>
</tbody>
</table>
Reconstruct all particles and combine the information from tracking with the measurements in the electromagnetic and hadron calorimeter → improve measurement of Jet energy, MET, Tau identification.

### Particles in jets

<table>
<thead>
<tr>
<th>Particles in jets</th>
<th>Fraction of energy in jets</th>
<th>Detectors</th>
<th>Single particle resolution (CMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charged Hadrons</td>
<td>65 %</td>
<td>Silicon Tracker</td>
<td>$\sigma_{pt}/p_t \sim 1%$</td>
</tr>
<tr>
<td>Photons</td>
<td>25 %</td>
<td>Elm. calorimeter</td>
<td>$\sigma_E/E \sim 2.8%/\sqrt{E}$</td>
</tr>
<tr>
<td>Neutral Hadrons</td>
<td>10 %</td>
<td>Elm. and had. calorimeter</td>
<td>$\sigma_E/E \sim 100%/\sqrt{E}$</td>
</tr>
</tbody>
</table>

Calorimetry only: $E_{\text{JET}} = E_{\text{ECAL}} + E_{\text{HCAL}}$

Particle Flow: $E_{\text{JET}} = E_{\text{TRACK}} + E_\gamma + E_n$
Particle Flow vs. pure Calorimetry

Jet energy resolution (MC):

MET distribution in $W \rightarrow e\nu$ candidate events (Data and MC):

Silicon trackers improve Jet, Tau and Missing $E_T$ measurements as well!
Conclusion

• All LHC experiments have installed large to very large silicon tracking systems - probably larger and more sophisticated than most optimistic physicists have dreamed 25 years ago!

• Silicon systems operating very successfull and stable with low number of dead channels – except various cooling problems – was this component underestimated?

• Physics performance reaching design figures and even better – see following talks.

THANK YOU FOR YOUR ATTENTION !