Detector R&D

Europhysics Conference on High-Energy Physics 2011

Grenoble, 26. July 2011

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Enormous world wide activity in particle detector R&D by:
- particle physics
- nuclear physics
- astro-particle science
- X-ray photon scattering science
- neutron scattering science
- medical/biological sciences

Almost impossible to keep overview and summarize all.
EPS-HEP2011 “Detector R&D” Session ~ 30 contributions

Please excuse personal selection based on ignorance and interest.

- Detector Performance of LHC experiments
- Improvements and Upgrades
- Challenges to Tackle
- Insights, Technologies & “driving” Developments
- Cute Ideas & Well Done

Apologies to those  
a) who do great work, but are not mentioned in my talk.
  b) who’s work is mentioned, but may not be correctly referenced.
Detector performance of LHC experiments

• Enormous growth ($\sim 10^5$) of LHC luminosity since startup

• Experiments constantly adapting
  - algorithms
  - FPGA firmware
  - DAQ software

• Problems showed up with rates!

• Low lumi periods allowed debugging

• Overall things have worked as planned!  
  $\rightarrow$ great success!

• High channel segmentation of experiments has paid off (so far)
  - operational channels (typ > 98% or better) & well calibrated

• Flexibility in detector specific, low level digital data manipulation by FPGA’s has been crucial to this success story.  
  $\rightarrow$ lesson for HL-LHC and other ambitions projects
CMS

- all sub-detectors in good shape
- well calibrated & aligned
- Trigger & DAQ runs ~100KHz
- Data taking efficiency ~93%

Silicon Strips  ~200m²
alive channels : 98%

Pixels  pixel size = 100µ x150µ
- alive pixel channels : 97%
- Pixel threshold = 2500 e
- in-time threshold ~3200 e
- analog pulse height readout
measured position resolution:
\( r_\phi = 12.7\mu +/- 2.3\mu \)
\( z = 28.2\mu +/- 1.9\mu \)
measured impact parameter (10GeV)
\( \delta (r_\phi) = 25\mu \)
\( \delta (z) = 45\mu \)
ATLAS

- work very well
- run efficiency 95.3% !

General Comment: remarkable agreement between Data – MC

e.g. Tile Calorimeter

**Pixels**  
pixel size = 50μ 400μ  
alive pixel channels : 97%  
meas. resolution:  ρφ = 19μ  z =115μ

Well adjusted pixel thresholds

Pulse-height by ToT

EPS Grenoble 26 July 2011
LHCb

- Luminosity leveling $\rightarrow L \sim 3 \cdot 10^{32} \text{ cm}^{-2} \text{s}^{-1}$
- Experiment operates well (at 50ns) with $\mu \sim 1.5$ beyond design of $\mu \sim 0.6$
- RICH works very well in complex events!

Remarkable little running inefficiency 1.4% due to VELO closing/opening to beam
ALICE

• Specialized on HI running but can do some things in pp

• 3 different silicon technologies

• **Silicon Drift Detector** unique!

Calibration / Alignment of Silicon Drift Detectors

Impact parameter at 1GeV measured $\delta (r\phi) \sim 60\mu$ !
ALICE

- Specialized on HI running but can do some things in pp
- 3 different silicon technologies
- **Silicon Drift Detector** unique!

Impact parameter at 1GeV measured $\delta (r\phi) \sim 60\mu$!
Improvements and Upgrades

• Data taking & physics analysis demonstrates shortcomings of experiments

• Upgrade decision are often problem driven. Many collaborators can convince themselves

• When it comes to the fix them, proposals quite often diverge again.

A few proposed upgrades with their solution are presented:

ATLAS Insertable B-Layer (IBL)

CMS Pixel Upgrade

LHCb & VELO Upgrades

Resistive MicroMega for ATLAS \( \mu \)-Chambers

CMOS Pixel Sensors for STAR
ATLAS IBL Upgrade

- FE-13 gets inefficient at HL-LHC
- new FE-14 ROC in 0.13µ CMOS
- new pixel size 50µ x 250µ
- chip shows excellent behavior
  - low pixel threshold ~1600 e
  - very rad. tolerant
  - low power (22µW/pixel)

Sensor options: planar n-in-n or 3D

Remarkable: planar sensor with ~200µ pixel to edge

trigger

in-pixel storage

trigger

storage

buffering

Triggered hits

data out
160Mb/s

Existing B-Layer

200µm

long pixel 500µm

pixel 250µm

“standard“
**CMS Pixel Upgrade**

Minimal changes to get a pin-compatible system

- Improve pixel vertexing in large PU events
  \[\rightarrow 3 \text{ layers to 4 layers}!!\]
- Shift material budget to high $\eta$ and use CO2 cooling
  \[\rightarrow \text{smaller impact parameter & less } \gamma \text{ conversion}\]
- Modify ROC to operate at $2 \times 10^{34}$ efficiently
  \[\rightarrow \text{reduce data loss as go beyond LHC luminosities}\]

**DC-DC converters**

- Buck Converter
  \[V_{\text{in}} \sim 12 \text{V}, \quad V_{\text{out}} \sim 2.5 \text{V}, \quad I_{\text{out}} < 2.8 \text{A}\]
  \[\text{efficiency } \sim 80\%\]

**$\mu$-twisted CCA pair**

- 1m long at 320MHz
- 3.125 ns
- 40mV

**Changes to ROC for $2 \times 10^{34}$**

- 40MHz analog $\rightarrow$ 160MHz digital
- 0.25$\mu$ CMOS, 5Metals $\rightarrow$ 6Metals
- increase depth of
  - data buffer 32 $\rightarrow$ 96
  - timestamps 12 $\rightarrow$ 24
- add readout buffer (64)
- add 8 bit ADC for pulse height
- lower pixel thresholds
- PKAM events $\rightarrow$ DAQ resync
3 layer pixel (old) with no PU same performance as 4 layer pixel (new) with ~40 PU

More pixel hits is essential for large number of PU events.
**LHCb & Velo Upgrade**

- 5fb⁻¹/year → 50fb⁻¹/year
- open access allows simpler change
- trigger limitations 1MHz → 40MHz
- software trigger with 20KHz output
- should deal with int. rate \( \mu \sim 2.1 \)

**VELO Upgrade Options:**

a) Strip detector: strip pitch 30µ
b) VELOPIX, Timepix based 55µx55µ pixel ROC, large data rates output

**PID Upgrade** (keep RICH-1 & RICH-2)

HPD’s with 1MHz ROC → MAPMT’s 40MHz

Under development @ Hamamatsu
ATLAS $\mu$-Chamber Upgrade

• Reduce forward muon fake rate
• several technologies considered, present:

Resistive MicroMegas

• designed for tolerating sparkes
• resistive strip parallel to readout strip

Prototype (9cm x 8cm) tested with neutrons $\sim 10^6$/cm$^2$. Shows no sparking compared to normal MM!

Technology is cheap $\rightarrow$ 200m$^2$

1.2m x 0.6m resistive MM
CMOS particle sensors

Use signal from ionizing particles in CMOS bulk.

- commercial standard CMOS process --> low cost
- signal collection by diffusion only → speed, spread
- typical signal ~ 1000 electrons on n-wells contacts
- typically few unipolar pixel transistors in p-well
- very small pixels with very low noise ~20 electrons
- rolling shutter to avoid random chip internal X-talk
- well suited for high precision & low rates
- 0-suppression in CMOS periphery → digital readout

STAR Pixel Upgrade (planned for 2014)

- 2 layers at 2.5cm / 8cm
- Mimosa 28 chip (“Ultimate”) in AMS-0.35μ CMOS
  - pixel size 20.7μ
  - chip size 20mm x 23mm
  - position resolution ~10μ
  - 200nsec per row scan
Challenges to Tackle

**HL-LHC Performance Estimates** (min. $\beta^* = 15\text{cm}$, CRAB cavities)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>nominal</th>
<th>25ns</th>
<th>50ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>1.15E+11</td>
<td>2.0E+11</td>
<td>3.3E+11</td>
</tr>
<tr>
<td>$n_b$</td>
<td>2808</td>
<td>2808</td>
<td>1404</td>
</tr>
<tr>
<td>Peak Luminosity</td>
<td>$1 \times 10^{34}$</td>
<td>$7.4 \times 10^{34}$</td>
<td>$6.8 \times 10^{34}$</td>
</tr>
<tr>
<td>Events/crossing</td>
<td>19</td>
<td>141</td>
<td>257</td>
</tr>
</tbody>
</table>

Physics analysis with many overlapping PU events is likely to suffer from

- **MET resolution**
- **jet energy resolution**
- **jet-jet separation**
- **Triggering problems**  → fast readout links are useful
Missing Transverse Energy with CMS

In CMS different methods to calculate Missing Transverse Energy (MET):

a) Calorimeter MET
b) Track-corrected MET
c) Particle flow MET (pfMET) → best results

Missing Transverse Energy can be faked by e.g. discharges or particle hits in photo-sensors! Was dealt with careful algorithms!

MET degradation vs. # PU events

How about 90 PU (2x10^{34}, 50ns)
High Granularity Particle Flow Calorimetry

Particle Flow Calorimetry has good chance to function even in with many PU events.

Basic Particle Flow Algorithm:
• Charged energy (65% in jet) – measure by tracking → separate multiple PU-events
• Photon (25% in jet) – precisely measured in ECAL
• neutrons / K_L (only 10% in jet) – measured in HCAL with moderate resolution
• Have to subtract away the charged energy in observed HCAL showers
• Confusion error in separation of showers is dominant
• Need a highly segmented HCAL detector → depth segmentation is crucial

CALICE AHCAL Prototype

• 38 layers with 2cm Fe (W since 2011)
• Scint. tiles with SiPM readout

PF-Calos scaling like ΔE/E ~ 3%
Insights, Technologies & “driving” Developments

**Silicon sensors** (basic material properties studies by RD-50)  
(U. Parzefall, U. Freiburg)

Irradiation in silicon sensors gives:

- Surface damage from Ionizing Energy Loss (IEL) $\rightarrow$ surface charges ($\text{SiO}_2$)
- Crystal damage from Non-Ionizing Energy Loss (NIEL) $\rightarrow$ energy levels in bandgap
  the latter leading to leakage current, trapping centers and doping effects.

$\rightarrow$ Type Inversion (doping)

Normalise dose $\Phi_{eq}$ to damage of 1-MeV-neutrons
Observe the generation of universal, device doping independent leakage currents.

Charge trapping is dominant radiation effect at $10^{15}n_{eq}$ and above!

\[
\tau_{eff}(10^{15}n_{eq}) = 2\text{ns}
\]
\[
\tau_{eff}(10^{16}n_{eq}) = 0.2\text{ns}
\]

\[
w = v_{sat}\tau_{eff} = 200\mu m
\]
\[
w = v_{sat}\tau_{eff} = 20\mu m
\]
Effective doping concentration $N_{\text{eff}}$ depends on radiation activated defects:

Epitaxial silicon diodes irradiated with:

- 23 GeV protons
- Reactor neutrons

Depending on radii, HL-LHC experiments will expose their silicon sensors more to charged hadrons or neutrons → pixels (more hadrons) & strips (more neutrons)
**Charge Collection in 3D Detectors**

- Short charge collection distance
-Insensitive regions for tracks passing through electrode pillars, e.g., 90° tracks
-Interleaved electrode pillars $\rightarrow$ capacitance!
-3D sensors show avalanche charge multiplication after irradiation. (seen also in planar)$\rightarrow$ non gaussian noise in electronics
Diamand Sensors

Particle detectors from Chemical Vapor Deposited (CVD) Diamond are trapping defect dominated.

Mono-crystalline diamonds show much better charge collection distances!

Mono- / Poly-crystalline Comparison

Mono-crystalline material shifted by \( 3.8 \times 10^{15} \) p/cm\(^2\) to mono-crystalline material

Running construction projects:
- ATLAS Beam Conditions Monitor
- CMS Pixel Luminosity Telescope
- ATLAS Diamond Beam Monitor
Cute Ideas & Well Done

DEPFET Vertex Detector for BELLE II

Belle II pixel vertex detector
- 2 layers at radii = 1.4, 2.2 cm
- monolithic sensor thickness 75μm
- pixel size ~50 x 50 μm²
- rolling shutter mode, 100nsec \(\rightarrow\) S/N=17/1

DEPDET Device Thinning Technology

Final device 75um thick \(\rightarrow\) \(X/X_0 = 0.18\%\) !!
(self supporting, no extra mechanics in sensitive region)
Si-Strip Tracker of the Fermi Large Area Telescope

J. Bregeon (INFN, Pisa)

Fermi Observatory with Large Area Telescope (LAT), Pair conversion $20\text{MeV} \rightarrow 300\text{GeV}$

- Si-strip/W pair conv. telescope, $1.5 \chi_0$
- $75 \text{m}^2$ Si-detectors in 18 planes
- Very stable operation observed
- Almost industrial production (9 month)
- $160\text{W}$ power consumption $\rightarrow 2\text{W/m}^2$
- Launched 2008, lots of data take

South Atlantic Anomaly (no data taking)

Galactic Center

Legend:
- No association
- Possible association with SNR or PWN
- AGN
- Pulsar
- Globular cluster
- Starburst Gal
- PWN
- HMB
- Galaxy
- SNR
- Nova
Edgeless Silicon Strip Sensors for TOTEM

- Very High Res. Si n-type (111)
- 300um thick, V_{dep} ~20V
- Standard planar technology
- Diamond saw dicing
- AC coupled strip

Sensitive strips 50µ close to edge!!

move very close to beam within Roman Pot.
Gaseous Pixel Detector

Gaseous Pixel detector (GridPix) is a MEMS made Micromegas like structure on a CMOS readout chip

Performance:
- position resolution: 15 μm
- single electron efficiency: > 90 %
- track detection efficiency: 99.6 %;

$^{90}$Sr electrons in 0.2 T B-field

μ-TPC operation with TimePix chip
Si-CdTe Compton $\gamma$-ray Camera

S. Takeda (ISAS/JAXA), TIPP2011

\[ \cos \theta = 1 - m_e c^2 \left( \frac{1}{E_2} - \frac{1}{E_1 + E_2} \right) \]

137 Cs (662 keV, 2.8 MBq)
SOI-CMOS Pixel Sensors

Silicon On Insulator (SOI) technology with 0.2µm CMOS process on Hi-R(Cz 700Ω·cm) / Low-R(Cz 18Ω·cm)

Buried P-Well(BPW) successfully solves back gate effect.

X-ray picture of a dry sardine

X-ray tube: Mo, 20kV, 5mA
Summary & Conclusions

• Detector Development is a fascinating and highly active field
• New detectors technologies offer new experimental opportunities
• Smaller experiments are quite often first system testers
• Role of micro-electronics is crucial
  - reduce costs of highly segmented systems
  - fast data links
  - fast timing in highly segmented systems
  - waveform sampling and digitization
  - flexible detector specific digital data manipulations (FPGA)
• Beam tests are vital to our community
• Detectors must be tested under equivalent conditions
• HL-LHC detectors need extensive high rate beam tests
• HL-LHC with many Pile-Up events will challenge calorimeter based physics analysis
• Tracker will bee crucial in this task → particle flow
  → combined tracker-calorimeter design
Thank you for your attention!