THE CMS PIXEL DETECTOR

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OUTLINE:

• Detector design, mechanics.

• Data rates, readout architecture.

• Simulation of the readout efficiency.

• Sensor development.

• Performance, possible pixel 2\textsuperscript{nd}/3\textsuperscript{rd} level triggers.

• Summary.
• 3D - tracking points

• $\sigma (z) \sim \sigma (r\phi) \sim 15\mu m$ for precise impact parameter in $r\phi$ & $z$

• **LAYERS:** $r = 4.3cm$  $7.2cm$  $11.0cm$

  Low Lumi  high Lumi

• replace layers after $6 \times 10^{14}/cm^2$

• all 3 layers compatible
CMS PIXEL BARREL

- Layer 1 & 2 & 3 mech. compatible

Mech. & Cooling
0.6% $X_0$

separate for insertion
BARREL PIXEL MODULE

- Silicon sensor $16 \times 64 \text{mm}^2$, $250 \mu\text{m}$ thick, $150\mu\text{m}$ square pixels
- 16 Readout chips (52 x 53 pixel) $\rightarrow \sim 44\text{k}$ pixel $\rightarrow 2.4$ Watt
- $\sim 1\% X_0$
## BARREL & FORWARD PIXEL

### Table 1: Parameters of CMS Pixel Barrel

<table>
<thead>
<tr>
<th>Layer</th>
<th>Configuration</th>
<th>Radius [mm]</th>
<th>Faces (*)</th>
<th>full/half Modules</th>
<th>Chips</th>
<th>Pixels</th>
<th>Area [m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 1</td>
<td>low lumi</td>
<td>41 - 45</td>
<td>18</td>
<td>128/32</td>
<td>2304</td>
<td>6.35 × 10⁶</td>
<td>0.15</td>
</tr>
<tr>
<td>Layer 2</td>
<td>low &amp; high lumi</td>
<td>70 - 74</td>
<td>30</td>
<td>224/32</td>
<td>3840</td>
<td>10.6 × 10⁶</td>
<td>0.25</td>
</tr>
<tr>
<td>Layer 3</td>
<td>high lumi</td>
<td>107 - 112</td>
<td>46</td>
<td>352/32</td>
<td>5888</td>
<td>16.2 × 10⁶</td>
<td>0.38</td>
</tr>
</tbody>
</table>

(*) Two half faces are counted as one face

### Table 2: Parameters of CMS Pixel End Disks

<table>
<thead>
<tr>
<th>z [cm]</th>
<th>Radius [mm]</th>
<th>Blades</th>
<th>Sensor Modules</th>
<th>Chips</th>
<th>Pixels</th>
<th>Area [m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>± 32.5</td>
<td>60 - 150</td>
<td>24</td>
<td>7</td>
<td>1080</td>
<td>3.0 × 10⁶</td>
<td>0.07</td>
</tr>
<tr>
<td>± 46.5</td>
<td>60 - 150</td>
<td>24</td>
<td>7</td>
<td>1080</td>
<td>3.0 × 10⁶</td>
<td>0.07</td>
</tr>
</tbody>
</table>
CMS PIXEL SENSOR

- Charge sharing by Lorentz effect \(\rightarrow\) position interpolation
- n\(^+\) pixel on n-silicon (initial)
- Operate partial depleted up to \(6 \times 10^{14}/\text{cm}^2\)

\[\left\langle B - \text{Field} \ (4 \ T) \right\rangle\]

\[n^+ - \text{pixel implants}\]

\[\text{Silicon} \ (p\text{-type})\]

\[\text{ionizing particle track}\]

- natural \(r\phi\) - pixel size \(\sim 150 \, \mu\text{m}\)
- position interpolation by analog readout \(\rightarrow\) \(\sigma (r\phi) \sim 10 \, \mu\text{m}\)
- need \(\sim 20000 \, \mu\text{m}^2\) pixel area for pixel circuit (transistors)
- defines \(z\) - pixel size \(\sim 150 \, \mu\text{m}\) \(\rightarrow\) good \(\sigma (z) \sim 17 \, \mu\text{m}\)
PIXEL DATA RATES

LHC high luminosity

1. **Tracks** :
   800 ( $\eta \leq 2$ ), $\leq 100$ (pT $> 1$ GeV).

2. **Pixels** :
   $4.6 + 3.3 + 2.5 + 1. + 1. = 13$ k pixels/event;
   e.g. @ 7 cm
   occupancy $\approx 3.3 \times 10^{-4}$;
   pixels/module $\approx 15$ (1 from noise);
   pixels/ROC $\approx 1$;
   single pixel rate $\approx 10$ kHz.

3. **Data volume** :
   13 k pixels * 3 Bytes $\approx 39$ kB/event;
   13 k pixels * 100 kHz $\approx 1.3$ G pixels/s
   * 3(10) Bytes $\approx 3.9(13)$ GB/s

4. **Double column**
   occupancy $\approx 1.5\%$;
   0.6 MHz column rate;
   2 pixels/column.

5. **Optical readout links** $\approx 3000$. 
READOUT OF TRIGGERED DATA

- Zero-suppression ----> data dependent readout time

Readout Time

<table>
<thead>
<tr>
<th>Radius /cm/</th>
<th>4</th>
<th>7</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROCs/link</td>
<td>8</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>&lt;pixels&gt;/link</td>
<td>16±11</td>
<td>15±9</td>
<td>8±6</td>
</tr>
<tr>
<td>&lt;readout-time&gt;/µs/</td>
<td>4</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>max. time /µs/</td>
<td>14</td>
<td>13</td>
<td>10</td>
</tr>
<tr>
<td>&lt;wait-time&gt;/µs/</td>
<td>1.4</td>
<td>2.4</td>
<td>1.1</td>
</tr>
</tbody>
</table>

(High luminosity, 40MHz link, 100kHz L1T rate)
PIXEL READOUT CHIP

Data flow of pixel hits in Column Drain Architecture
**COLUMN PERIPHERY**

- Dual-ported hit buffer (Column Drain --> Chip Readout)
- Time-stamp verification with T1 trigger
- Data formatting and readout of T1-verified hits with analog coded pixel address header
- Prototype circuit: DM_PSI35 (DMILL) Dec. 98
Number of pixels per data packet and the packet readout time for the 7cm pixel layer at high and low LHC luminosities.
Number of ROCs/link = 16, link speed = 40MHz, L1T rate = 100kHz.
The Token-Bit-Manager (TBM) chip has to queue the incoming 1st level triggers.

Trigger stack for the pixel barrel at 4cm and 7cm, LHC high luminosity:

The TBM stack counter occupancy. The solid line is for 100kHz 1LT rate, the dashed line is for 30kHz.
Data loss for the pixel barrel at 7 cm

**BLUE**: high-lumi, 1LT 100kHz, 40/20MHz link.

**RED**: high-lumi, 1LT 30kHz, 40/20MHz link.

**GREEN**: low-lumi, 1LT 100kHz, 40/20MHz.

**BLACK**: low-lumi, 1LT 30kHz, 40/20MHz.
**READOUT DATA LOSS**

Pixel Barrel Layer at 7cm, full LHC luminosity

Sources of data loss:

1. Column readout losses e.g. pixels overwritten, column busy, time-stamp and data buffers full.
2. Readout data buffer overflow, a column can store only one 1LT trigger confirmed time stamp.
3. After readout the column is reset, all time stamps are lost.
4. Dead time of 1 clock (25ns) to setup the column readout mechanism after this column was hit.
SEONSOR DEVELOPMENT

Status at the time of the CMS Tracker TDR:

- Si sensors irradiated up to $6 \times 10^{14}$ pion/cm$^2$,
- After some annealing time (~1 year) can be depleted to 200 µm at -300V bias voltage (14 ke signal).

Recent progress, future plans:

- Test new sensors received from CSEM and SINTEF, low and high resistivity wafers, standard and oxygen enriched.
- Variations in:
  - p-stop rings, n implant size, # of p-stop rings, guard-rings, ….
- Irradiation (April 2000 at CERN).
- Beam tests with bump-bonded detectors (fall 2000), overall optimization program.
- Summer-Fall 2001 selection of the final design.
SILICON SENSOR PERFORMANCE

after 6 x 10^{14}/cm^2 300 MeV/c pions at PSI

- expect at least **14000** electrons signal up to 6x10^{14}/cm^3
- need **2000 - 3000** e pixel threshold for analog interpolation

**Goal:**

- run with **2500** e pixel threshold
- **5σ** noise threshold ----> noise < **500** e

also after irradiation!
Inter-pixel current as a function of bias voltage.
SOME COMMENTS ABOUT THE PERFORMANCE

Despite the somewhat different designs both detectors Atlas and CMS show very similar simulated performance.

→ See the LHC physics yellow report, e.g. $\text{Bs} \to J/\Psi(\mu\mu) \Phi(KK)$

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events</td>
<td>300000</td>
<td>300000</td>
</tr>
<tr>
<td>Time resolution</td>
<td>0.063 fs</td>
<td>0.063 fs</td>
</tr>
<tr>
<td>Background</td>
<td>15%</td>
<td>10%</td>
</tr>
</tbody>
</table>

How could the pixel detector be used in triggering?

- 3\textsuperscript{rd} level CMS trigger involves full event reconstruction and the pixel detector is fully included;
- Can one do something at the 2\textsuperscript{nd} level with a "standalone" pixel detector information?
Pixel Barrel Layer at 7cm

Hits from 100 GeV \( \mu \) tracks.

**r\( \phi \) direction**

<table>
<thead>
<tr>
<th>Rapidity</th>
<th>Resolution [( \mu \text{m} )]</th>
</tr>
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<tbody>
<tr>
<td>0.5</td>
<td>200-125</td>
</tr>
<tr>
<td>1</td>
<td>300-150</td>
</tr>
<tr>
<td>1.5</td>
<td>300-125</td>
</tr>
<tr>
<td>2</td>
<td>150-125</td>
</tr>
<tr>
<td>2.5</td>
<td>250-150</td>
</tr>
<tr>
<td>3</td>
<td>250-125</td>
</tr>
</tbody>
</table>

**z direction**

<table>
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<th>Resolution [( \mu \text{m} )]</th>
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PIXEL HIGH LEVEL TRIGGERS

THE ALGORITHM

• Correlate hits in two pixel layers which point in $\phi$ and $z$ to the interaction region.

• Match hits in $\phi$ and $z$ in the 3$^{rd}$ pixel layer.

• Find the PV (histogramming the $z$ impact parameter) and eliminate track candidates which do not point to it.
PIXEL TRACK FINDER

Efficiency for track finding using the 3 pixel layers only.
The difference (in cm) between the z position of the Monte Carlo primary vertex and the reconstructed primary vertex. Only pixel hits are used in the vertex reconstruction. The upper plot is for qcd-jet events at high luminosity with the 3 layer pixel barrel. The lower plot is for same events at low luminosity and with a 2 layer pixel barrel. The dashed line shows all found vertices and the solid line is the main "signal" primary vertex as found by the algorithm.
SUMMARY

CMS pixel collaboration:

- **Readout chip**: PSI, RWTH Aachen, ETHZ,
- **Sensors**: PSI, Uni. Zuerich,
  Purdue Uni., Johns Hopkins Uni.,
- **TBM chip**: Rutgers Uni.,
- **Bump bonding**: PSI, ETHZ, UC Davis,
- **Trigger**: PSI, Uni. Basel,
- **Control**: PSI, Uni. Basel, Fermilab,
- **Mechanics, cooling**: PSI, Uni. Zuerich,
  Northwestern Uni., Uni. of Mississippi,
- **VME readout**: HEPHY Wien,