The CMS Silicon Strip Tracker - Overview and Status

Katja Klein

1.Physikalisches Institut B, RWTH Aachen

Overview

- Requirements for tracking at the LHC & expected performance of the CMS tracker
- The design of the CMS silicon strip tracker
- Experience from mass production and detector integration
- Challenges and issues
- Measurements, e.g. from test beam experiments and integration
- Aachen involvement

- Track & laser alignment → Martin Weber, 2.2.2006
Silicon Strip Detectors

- Reverse-biased diode
- MIP ionizes detector material: 24000 e\textsuperscript{-} in 300\textmu m of silicon
- Electric field $\rightarrow$ electrons and holes drift to electrodes
- Segmented p-implants in n-type bulk $\rightarrow$ spatial information
- AC-coupled read out of induced charge
- Signal amplification and shaping
First silicon strip detector:
- NA11 in 1983: 5μm spatial resolution

Comparison of some silicon strip detectors:

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Number of detectors</th>
<th>Number of channels</th>
<th>Silicon area [m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aleph</td>
<td>144</td>
<td>95000</td>
<td>0.49</td>
</tr>
<tr>
<td>CDF II</td>
<td>720</td>
<td>405000</td>
<td>1.9</td>
</tr>
<tr>
<td>D0 II</td>
<td>768</td>
<td>793000</td>
<td>4.7</td>
</tr>
<tr>
<td>AMS II</td>
<td>2300</td>
<td>196000</td>
<td>6.5</td>
</tr>
<tr>
<td>Atlas</td>
<td>4088</td>
<td>6300000</td>
<td>61</td>
</tr>
<tr>
<td>CMS</td>
<td>15148</td>
<td>10000000</td>
<td>200</td>
</tr>
</tbody>
</table>
The Large Hadron Collider (LHC)

First collisions in 2007

<table>
<thead>
<tr>
<th>Beams</th>
<th>Energy</th>
<th>Luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEP</td>
<td>$e^+e^-$</td>
<td>200 GeV</td>
</tr>
<tr>
<td>LHC</td>
<td>$p\bar{p}$</td>
<td>14 TeV</td>
</tr>
<tr>
<td></td>
<td>$P_b\bar{P}_b$</td>
<td>1312 TeV</td>
</tr>
</tbody>
</table>
Staged commissioning plan for protons

I. Pilot physics run
   - First collisions
   - 43 bunches, no crossing angle, no squeeze, moderate intensities
   - Push performance (156 bunches, partial squeeze in 1 and 5, push intensity)
   - Performance limit $10^{32}$ cm$^{-2}$ s$^{-1}$ (event pileup)

II. 75ns operation
   - Establish multi-bunch operation, moderate intensities
   - Relaxed machine parameters (squeeze and crossing angle)
   - Push squeeze and crossing angle
   - Performance limit $10^{33}$ cm$^{-2}$ s$^{-1}$ (event pileup)

III. 25ns operation I
   - Nominal crossing angle
   - Push squeeze
   - Increase intensity to 50% nominal
   - Performance limit $2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$

IV. 25ns operation II
   - Push towards nominal performance

(L. Evans, December 2005; CMS Physics TDR)
The Compact Muon Solenoid (CMS) Experiment

pixel detector and silicon strip tracker

21.6m

21.6m

15m

Electromagnetic calorimeter:
80,000 PbWO$_4$ crystals
$A=2.2\times2.2\text{cm}^2$
$X_0=0.89\text{cm}$

Hadronic sampling calorimeter:
copper and scintillating tiles

Superconducting solenoid, $B=4\text{T}$

Muon chambers (in magnet return yoke):
drift tubes (barrel), cathode strip chambers (end caps) and RPCs (barrel and end caps)
Tracking Requirements at the LHC

- Bunch spacing of 25ns → **fast detector response** to resolve bunch crossings
- High luminosity ($2 \cdot 10^{33} - 10^{34} \text{ cm}^{-2} \text{s}^{-1}$)
  ⇒ up to 20 minimum bias and 1000 charged particle per bunch crossing
  → **high detector granularity** to keep occupancy low and resolve nearby tracks
- **Good momentum resolution** for low and high-$p_T$ tracks
- **High track reconstruction efficiency**
- Ability to tag b-jets and identify B-hadrons and $\tau$'s
  → **good impact parameter resolution**
- Unprecedented irradiation level → **radiation hardness**
- Small amount of material in front of electromagnetic calorimeter
- Cost
- Risk of failure (preference for known industrial technologies)

⇒ Major design change in the CMS tracker in 1999
  Multi-strip gas chambers (MSGCs) dropped in favour of all-silicon tracker
About 200m$^2$ of active silicon area
- 1440 pixel modules with 66 million pixels
- 15148 silicon strip modules with \( \approx 10 \) million strips
- Operating temperature \(< -10^\circ C\) to minimize radiation damage (max. dose for strip tracker after 10 y \( \equiv 1.6 \times 10^{14} n(1\text{MeV}) / \text{cm}^2 \)
The CMS Pixel Detector

- **Start with 2 barrel layers in 2008**
  \((r = 4.4 \text{ cm} & 7.3 \text{ cm})\)
- **Add 3. barrel layer later** \((r = 10.2\text{cm})\)
- **Two turbine-like endcap disks side**

- Active area \(\approx 1\text{m}^2\)
- 66 million pixels
- Pixel size: \(100\mu\text{m (r-}\phi\text{)} x 150\mu\text{m (z)}\)
- Charge sharing due to large Lorentz angle \((23^\circ) + \) analog readout
  \(\rightarrow \text{spatial resolution } \approx 10\mu\text{m in r-}\phi, \approx 20\mu\text{m in z}\)

\(\Rightarrow 2\text{-}3 \text{ high resolution 3d measurement points}\)
The CMS Silicon Strip Tracker

Schematic cross section of one quarter of the tracker:

- **single-sided modules**
- **double-sided modules** (stereo angle = 5.7°)
  → position information along the strips

**TOB:**
6 layers
5208 modules

- **thick sensors:** 500µm
- **high resistivity**

- **thin sensors:** 320µm
- **low resistivity**

**TIB:**
4 layers
2724 modules

**TID:**
2 x 3 disks
816 modules

**TEC:**
2 x 9 disks
6400 modules

Katja Klein
The CMS Silicon Strip Tracker

11/46
- Conversion probability for photons almost 50%
- Material budget dominated by services
# of hits per track in the strip tracker:

- total number of hits
- total number of double-sided hits
- double-sided hits in thin detectors
- double-sided hits in thick detectors

⇒ At least 10 measurement points, except for region between barrel and end cap

Transverse momentum resolution for muons with $p_T = 1$ GeV, 10 GeV, 100 GeV:

⇒ Resolution dominated by tracker lever arm
⇒ Barrel: resolution of 1.5% for $p_T = 100$ GeV
Performance of the CMS Tracker

**Transverse impact parameter res.**
for muons with $p_T = 1, 10, 100$ GeV:

- Dominated by hit resolution and, for $p_T < 10$ GeV, multiple scattering
- For tracks with $p_T = 100$ GeV: 10$\mu$m transverse and 20-50$\mu$m longitudinal impact parameter resolution

**Longitudinal impact parameter res.**
for muons with $p_T = 1, 10, 100$ GeV:
Comparison: the Atlas Tracker

Pixel:
- 3 barrel layers, 2 x 3 disks → three 3-d space points for 98% of tracks
- Spatial resolution ≈12 μm in r-φ, ≈ 60 μm in z

Semi-conductor tracker (SCT):
- 4 barrel layers, 2 x 9 disks; 4088 modules, 61 m²
- All modules are double-sided (2.3°)

Transition radiation tracker (TRT):
- 370 000 drift tubes; spatial res. from drift time: 170 μm per straw
- Continuous tracking (> 30 hits per track), low cost, less material per point
- Electron/pion separation
- Concerns: occupancy, speed (maximal drift time: 40 ns)

Tracking performance similar to CMS tracker!
The CMS Silicon Strip Modules

- glass pitch adapter
- 1 or 2 silicon sensors
- support frame
  - graphite and carbon fiber (CF)
- front-end (FE) hybrid
- wire bonds
- Kapton circuit
  - delivers bias voltage
  - back plane isolation
  - thermistors
- direction of strips

≈10cm
Module design optimised for geometrical coverage, radiation hardness & cost

→ 27 different module types:

- $r < 60\text{cm}$: - 320$\mu$m thin low resistivity sensors (lower depletion voltage after irradiation);
  - shorter strips (occupancy)
- $r > 60\text{cm}$: - longer strips (cost);
  - 500 $\mu$m thick (high resistivity) sensors to maintain signal / noise
- 1 or 2 silicon sensors
- 512 or 768 strips
- rectangular sensors in the barrel, wedge-shaped sensors on the disks

Atlas: 4 types of modules (1 in barrel, 3 in end caps); all 285 $\mu$m thick
• Single-sided sensors with p\(^{+}\)-type strips in an n-type bulk
• 6" wafer technology (Atlas: 4")
• <100> cristal lattice orientation (→ interstrip capacitance unchanged after irradiation)
• AC-coupled readout
• Pitch ranges from 80-210\(\mu\)m
• Constant width/pitch (→ constant strip capacitance)
• Readout strip and guard ring geometries optimised to increase breakdown voltage
Design of the CMS Silicon Sensors
24,244 silicon sensors have been delivered by two companies:
- 320µm thick sensors by Hamamatsu Photonics K.K. (HPK);
- 500µm thick sensors: 96% by HPK and 4% by ST Microelectronics (STM)

Sensor production is completed!
Silicon Sensors: Issues

Many problems with STM sensors encountered:

Unstable leakage current:

High noise on single strips, plus high common mode of the whole readout chip (128 strips):

Electrochemical changes (corrosion) on bias and guard rings after few hours in high humidity:

⇒ quality test of 100% of STM sensors necessary, long-term behaviour and evolution unknown

⇒ bulk of production of thick sensors was transferred to HPK
The Front-end Hybrid

4-layer Kapton substrate (flex) laminated onto ceramic carrier

4 or 6 APV25 readout chips
- radiation hard commercial 0.25µm CMOS technology
- 128 strips per APV, multiplexed to one analog output
- per channel: pre-amplifier, CR-RC shaper, 4.8 µs pipeline memory

2 readout modes:
- Peak mode: 1 sample (τ≈50ns)
- Deconvolution mode (high lumi):
  weighted sum of 3 samples: τ≈25ns
  → better bunch crossing identification, but higher noise

2:1 Multiplexer
- 2 APVs multiplexed to one readout channel

PLL chip
- decodes clock & trigger signals

Detector Control Unit (DCU)
- 12-bit ADC
- 8 channels:
  - hybrid and sensor temperatures
  - low voltages
  - leakage current

Katja Klein
The CMS Silicon Strip Tracker
Why to use analog readout?

**CMS:** analog readout ⇒ information on deposited charge
- Multi-strip clusters: center-of-gravity method leads to improved position resolution
- dE/dx measurement (?)
- Larger data volume
- Needs analog optical* links (not standard few years ago)

**Atlas:** binary readout ⇒ only hit/no-hit information
Strip with charge above adjustable threshold fires discriminator on front-end chip
- Reduced data volume (cost effective)
- Works with standard digital optical links
- Spatial resolution = pitch/√12 (pitch=80μm ⇒ σ(rφ)=23μm)
- Thresholds, discriminator, noise must be well controlled
- No common mode subtraction possible

*Advantage of optical readout: low mass, no electrical pick-up
Front-end Hybrid Production

- **Very long R & D phase with many different technologies developed in parallel**
  (thick-film on ceramic, full flex Kapton on CF or FR4, flex-rigid, pure FR4, ...).
  Problems: flatness ($\rightarrow$ assembly), rigidity ($\rightarrow$ bonding), thermal exp. coeff. mismatch, feature size ...

- **2003 technology choice & start of mass production**

- **Flex circuits produced by Cicorel SA, assembly done by Hybrid SA**

**Several problems during production phase, e.g.:**

100$\mu$m vias developed bad contact $\rightarrow$ solved by improved design (8 months delay)

- Finally a production rate of 300-400 hybrids/week was achieved
- A second production line (different flex producer, different assembler) was set up

**Production nearly completed**
Module Production

- 27 types of modules
- 15 types of sensor masks
- 24 types of pitch adapters
- 12 types of hybrids
- 19 types of frames
Module Production: Assembly

- Module assembly = precision gluing of sensor(s) and hybrid to the support frame
- 15148 modules need to be assembled with high precision:
  - e.g. maximum allowed deviation in coordinate \( \parallel \) strips: 65\( \mu \)m, coordinate \( \perp \) strips: 39\( \mu \)m
  \( \Rightarrow \) fully-automatic pick-and-place robots: “gantry”

- 6 gantries in operation
- Issues: precision, calibration
- 99% of modules are within specification
- Throughput: up to 20 modules / gantry / day
Module Production: Wire Bonding

- 23 automatic commercial wire bonding machines
- Throughput: > 5 modules / machine / day
- Readout tests before and after bonding
- Pull tests to monitor bond strength

Sample of Pitch Adapter-Sensors bonds

5g

Mean force [g]

Sample of Pitch Adapter-Sensors bonds

Counts

Sigma/mean of pull force

20%

Sigma/mean of pull force

Katja Klein

The CMS Silicon Strip Tracker
• **Excellent module quality:** typically 1-3‰ of bad strips per module
• However: backplane contact (conductive epoxy glue) not reliable (TOB, TEC)
  ⇒ "Retro-fitting" of significant number of modules ongoing

⇒ In total, 75% of modules are built
⇒ End of module production expected for spring 2006
Readout and Control Architecture

**Readout:** *analog* optical link

- **FE hybrid**
  - Detector Hybrid
  - APV amplifiers
  - pipelines
  - 128:1 MUX
    - PLL
    - DCU
- **AOH**
  - A-Opto Hybrid
  - opto-electrical conversion
- **optical link**
  - 10 bit ADC (Front End Driver)
  - FED
  - Rx Module
  - processing
  - buffering
  - DAQ
- **control chips on substructures**
  - Control
    - CCU
  - DOH
  - CCU
  - D-Opto Hybrid
  - CCU
- **Front End Controller**
  - FEC
  - TTCRx
  - processing
  - buffering

**I²C protocol**

**Trigger, clock, control signals:** *digital* optical link (token ring implementation)
Digitization (10 bit) and first data processing:
- pedestal and common mode subtraction
- cluster finding
- optional zero suppression to reduce data volume
- storage of data until requested by higher DAQ

• developed at RAL
• double-sided VME64x card (9 units height)
• optical / analogue / digital logic
• 14 layers, 6,000 components, 25,000 tracks
• input data volume 3GB/sec, reduced to 50MB/s per % of track occupancy

Status:
• 110 / 500 FEDs delivered to CERN
• Still many firmware improvements
  (debugging capabilities, data rate increase, readout stability)
Modularity in the Tracker

**TIB/TID:** modules are mounted directly onto half-shells and carbon fiber ring structures

**TOB:** modules are assembled onto "rods", rods are mounted into the "wheel"

**TEC:** modules are assembled onto carbon fiber "petals", petals are mounted into the end caps

**Advantage of TOB/TEC approach:** single substructures can be exchanged during shutdowns

**Disadvantage:** no access to modules once substructures are integrated into wheel / end cap
Example: TEC Petal production

288 petals to be built until mid 2006

- up to 28 silicon modules
- up to 10 different types
- up to 28 AOHs
- up to 13 types

ca. 400 assembly pieces of 32 diff. types: "bridges", washers, screws, distance pieces

frame + Kapton strip
hybrid + pitch adapter
sensor
petal mechanics
motherboards (ICBs)
**Mechanical petal structure:**

- Honeycomb structure with CF skins: light but stiff  
  (developed and built in Aachen)

- Modules mounted on 4 aluminum precision inserts  
  (precision of thread positions: 5µm)

- Modules cooled to $T < -10 \, ^\circ C$ (reverse annealing)  
  via 7m long thin walled titanium cooling pipe  
  (coolant: $C_6 F_{14}$)

**Motherboards (InterConnect Boards, ICB):**

- "Backbone" of the petal: 6 layer PCBs
- ICBs are developed, tested and mounted in Aachen

**Petal production until February 2006**
Petal Assembly

- Two petal types: front and back petals
- Modules are mounted on both sides of the petals in (up to) 7 radial rings
- Rings overlap in the radial direction, modules overlap in $\phi$
- Mounting of optical converters (AOHs), routing of fibers, functional test (Hamburg)
- Assembly of modules and functional test (7 prod. lines in 5 centers, Aachen & KA)
  Operator is guided by special software with photos, drawings & automatic data base operations

**Difficulties:**
- handling
- application of thermal grease

**Achieved assembly rate:** > 2 petals / week / production line
Petal Longterm Test

- "Burn-in" of components & connections at level of petal
- 6 cooling cycles between room temp. and -20°C → 3 days in total
- In-depth qualification of petals
- Grading
- Longterm testing of fully assembled petals started May 2005
- **Quality of petals produced is very good: 1-3 % of bad strips**

Status:
- 5 lines operational with a capability of 1 petal / setup / week
- 100 / 300 petals already longterm tested
May 2004 test beam setup:
1 front and 1 back petal (≈ 1% of the TEC), operated at CMS temperature (≈ -10°C)

pions (120GeV)
muons (70GeV-120GeV)

Typical distributions (shown for a ring 4 module on the back petal):
Some highlights:

- S/N > 19 for all rings at CMS operating temp.
- Decrease by at most 25% due to radiation damage.
- S/N > 10 guarantees hit finding efficiency above 95% and low fake rate.

- Variation between rings as expected from capacitance.
- Agrees within 17% with expectation from APV noise.
- Noise about 10% smaller at CMS operating temp.
- Common mode noise:
  - peak mode: \((173 \pm 38)\) e\(^{-}\)
  - deconvolution mode: \((299 \pm 67)\) e\(^{-}\)

Katja Klein

The CMS Silicon Strip Tracker
Tracker Outer Barrel (TOB) Rod Production

- Modules mounted onto 688 rods
- 100% of rod frames produced
  (precision of positioning pins: $\sigma = 40\mu$m)
- Redesign of motherboards due to electrical problem
- Rod assembly & 1-2 days longterm test
  (Fermilab & UCSB)

Status:
- Rod assembly delayed by problems with module bias contact & motherboard redesign
- About 70 rods assembled and longterm tested in "production exercise"
- Rod assembly much easier than petal assembly
- Expected production rate: 4 rods assembled & longterm tested per day and site
  $\Rightarrow$ all TOB rods can be built within 4-5 months
TEC Integration - Overview

- 8 petals mounted on each side of the carbon fiber disks, 9 disks per end cap
- Both mechanical structures built in Aachen, precision (CERN photogrammetry) < 200μm
- All optical ribbons integrated (Karlsruhe)
- Cooling pipes with power cables still in production (issues: precision, weld joints) (Lyon)
- One end cap ("TEC+": +z direction) to be integrated in Aachen
- Second end cap to be integrated at CERN by Lyon group
• **Petals are integrated sector-wise**
• Integration with TEC in upright position
• Petals mounted with 3-point-fixation; precision of module position w.r.t. disk: $50\mu m$
• Disks used as “desk” during insertion $\rightarrow$ need possibility to rotate the TEC

1 sector ($=18$ petals):
1 tower of back petals (9 petals)
1 tower of front petals (9 petals)
TEC Integration: Overview

- One year of preparation!
- Dedicated 50m$^2$ clean room built (class 100 000)
- Rotation and transport cradle designed and constructed
- Data acquisition system with final hardware components for 400 modules installed and commissioned (3% of the whole tracker) (48 final CAEN power supply units, 11 FEDs)
- 2.4km $\approx$ 1t of final power cables installed
- Cooling system for CMS coolant ($C_6F_{14}$) constructed
Integration of the First Sector

During December/January, the first sector has been integrated in Aachen
All procedures have been validated and tools have been commissioned

Petal insertion:

- tool was developed to handle petals safely
- insertion of 1 petal needs about 40 minutes
- most time-consuming task: plugging of optical fibers (≈ 50 per petal)
First TEC Sector

- Very dense environment
- Difficult access to fibers, no access to silicon modules
- In situ debugging & repair is difficult and in many cases impossible
• System of 400 modules = 1092 optical channels debugged (half of CDF SVX II) on level of bare connections
• Basically impossible without dedicated commissioning tools
• First pedestal runs with high voltage taken last week
• Too early to make any statements about the noise (unfortunately)
• Large measurement program ahead: cosmic, grounding, cold test ...

**TEC integration is the first opportunity for measurements of petals in close-to final environment with many final components**
(cables, power supplies, DAQ, grounding, ...)

**Exercise tracking and laser & track alignment in a final environment**
(talk by Martin Weber)
**TIB/TID Integration**

- **Strings of 3 single- or double-sided modules mounted on inner & outer surfaces of half-shells**
- Functional test of strings, longterm test of entire half-shells
- Two outer layers (single-sided) of TIB+ fully integrated
- **First layer has been longterm tested (315 modules):** < 1‰ of bad channels
- Integration of double-sided layers has started
- TIB+/TID+ shall be brought to CERN in February

**Noise [ADC counts]**

<table>
<thead>
<tr>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
<th>$\chi^2 / \text{ndf}$</th>
<th>Constant</th>
<th>Mean</th>
<th>Sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>81408</td>
<td>2.777</td>
<td>0.2296</td>
<td>741.5 / 25</td>
<td>2.187e+04 ± 93</td>
<td>2.774 ± 0.001</td>
<td>0.2207 ± 0.0005</td>
</tr>
</tbody>
</table>

**Deconvolution mode**

<table>
<thead>
<tr>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
<th>$\chi^2 / \text{ndf}$</th>
<th>Constant</th>
<th>Mean</th>
<th>Sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>79572</td>
<td>3.903</td>
<td>0.3686</td>
<td>1663 / 42</td>
<td>1.417e+04 ± 62</td>
<td>3.891 ± 0.001</td>
<td>0.3302 ± 0.0008</td>
</tr>
</tbody>
</table>
The CMS tracker is a very complex subdetector with many challenges.
Measurements performed up to now show excellent performance.
75% of modules are built.
Integration of TIB/TID and TEC has started.
Integration into the CMS detector foreseen for early 2007.
On-time delivery of the tracker seems still possible.
Looking forward to do interesting physics with a performant tracker.

$\tilde{\chi}_2^0 \rightarrow Z^0 \tilde{\chi}_1^0$