Operation and Performance of the CMS Silicon Strip Tracker

Gero Flucke
(on behalf of the CMS Collaboration)

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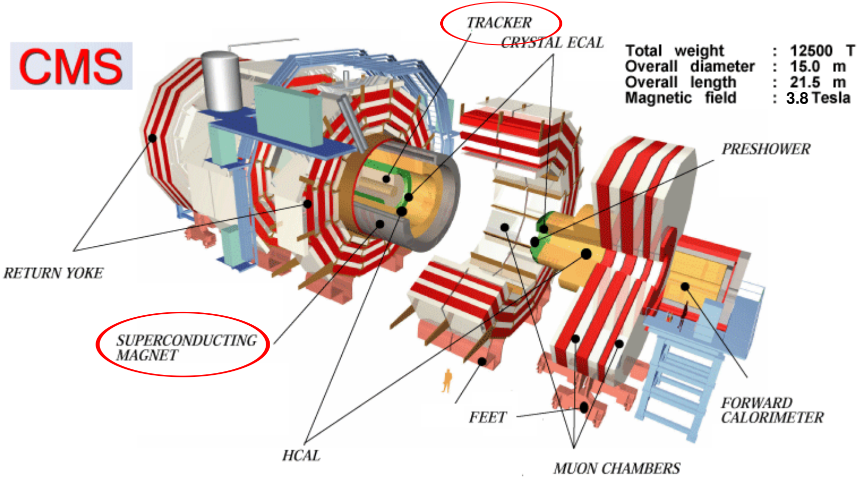
Operation and Performance of the CMS Silicon Strip Tracker

Outline

- CMS silicon strip tracker:
  - modules, readout, services
- Operation issues
- Detector performance
- Alignment

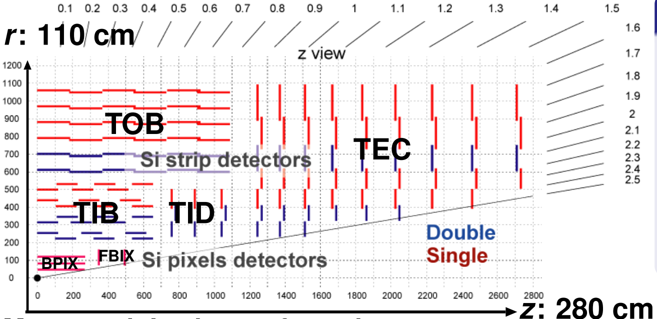
The CMS Detector at the LHC



- Large solenoid: $B = 3.8$ T.
- All silicon tracker: $\sigma(p_t)/p_t = $ 1-2% for $p_t(\mu) = 100$ GeV/c.

The CMS Tracker: All Silicon

rz-view (upper right quarter)



Strip Sensors

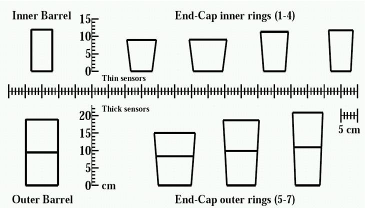
$20 < r < 55$ cm, thin:

- $d = 320\ \mu$m

$r > 55$ cm, thick:

- $d = 500\ \mu$m
- 2 sensors

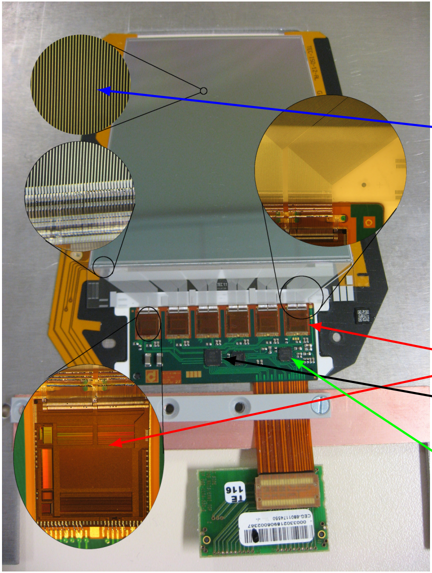
Many module shapes for strips



- 9.6 M strips in 15 148 modules.
- 200 m^2 silicon sensors.
- Strips generally measure $r\phi$ direction.
- Some radii ('Double'): additional 2nd modules rotated by 100 mrad $\Rightarrow$ measurements for η(track).

CMS Silicon Strip Modules

TEC Ring 1 Module



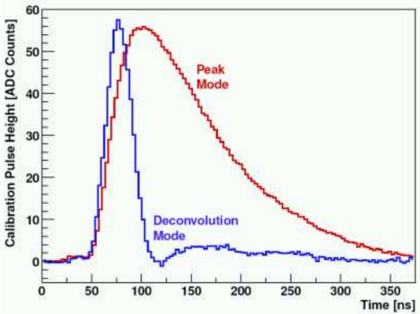
Sensor

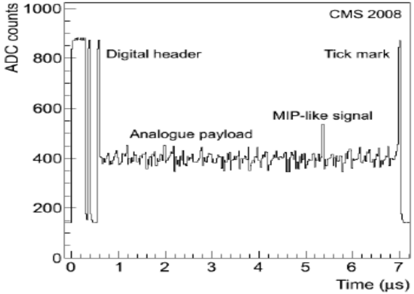
- p^+ implant in n-type silicon bulk (single-sided processing [⇒]).
- 512 or 768 strips.
- strip pitch p=80-205 μm.
- $\frac{w}{p} = 0.25$ (w: p^+ implant width).
- AC-coupled readout.

Electronics on Hybrid

- 4 or 6 APV readout chips.
- Multiplexed on 2 or 3 readout lines by **MUX**.
- DCU: leakage current, temperature,...

Readout





APV Chip

- **Analog** readout every 25 ns.
- 192 cell pipeline ($\widehat{=}$ 4.8 μs).
- Peak mode (signal height p),
  - CR-RC circuit (50 ns),
  - low noise,
  - robust for time misalignment.
- Deconvolution mode,
  - signal at t is weighted mean: $d_t = w_3 p_{t-2} + w_2 p_{t-1} + w_1 p_t$
  - shorter signal,
  - higher noise.

Signal Frame: 2 APVs Interleaved

- Headers and tick marks frame 2×128 analog signals.
- Send on external trigger.

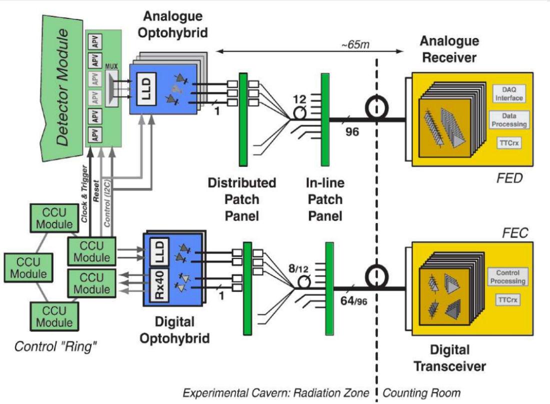
Readout and Control Chains

Signal Path (upper half)

- Module: silicon ⇒ APV ⇒ MUX
- AOH (electric → light)
- Fibre
- FED

Control Rings (lower half)

- FEC
- Fibre
- DOH (electric ↔ light)
- CCU
  - ⇒ clock/trigger ring
  - ⇒ I^2C communication
- Module (APV, DCU)



440 FEDs

- Non-zero suppressed data from fibre.
- Digitisation, common mode noise subtraction, zero suppression.

⇒ Rely on pedestal and noise values.

Services Work Reliably

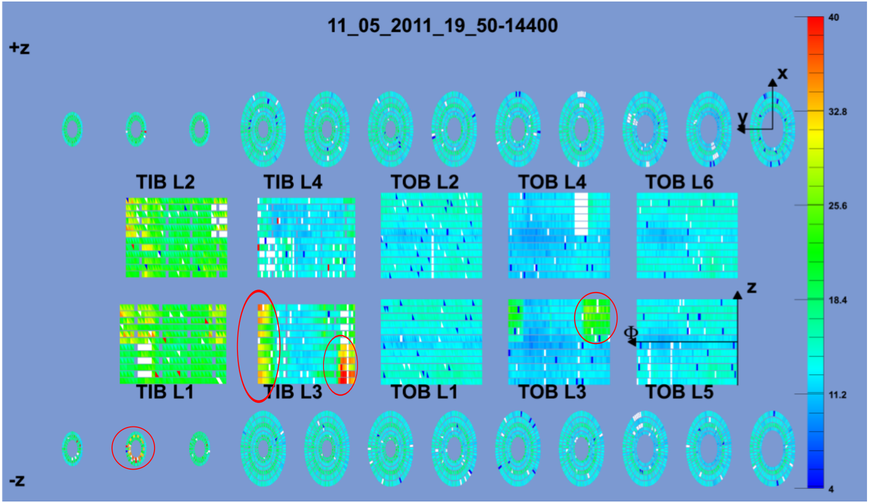
Power Supply (PS)

- Inside cavern (in contrast to FEDs/FECs):
  - to reduce losses in copper cables,
  - requires radiation and B-field tolerance.
- 1944 PS units (2 per PS module) for silicon modules:
  - 1 LV line (1.25 V, 2.5 V) for APV, AOH,...
  - 2 HV lines (up to 500 V, now at 300 V), 3-12 silicon modules each,
  - failure rate even smaller than in previous years (<1% per year).
- 356 LV power groups for control rings: no group failed yet.

Cooling

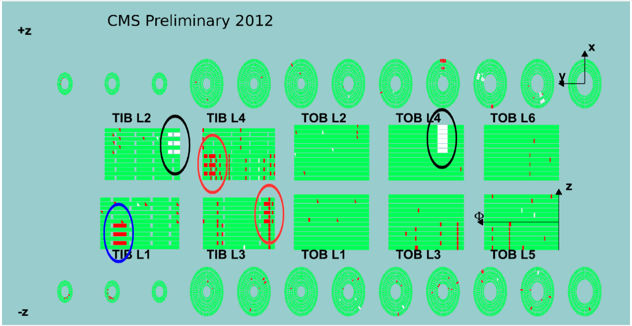
- Need to take away about 50 kW.
- Two cooling plants for strip tracker, 90 lines each.
- Cooling liquid is C_6F_{14}: volatile, neutral to electronics.
- Leaks not an issue anymore: ~1 kg per day (five lines closed).
- Cooling liquid at 4° C,
  - to be decreased significantly in 2013/14 shutdown:
  - essential to mitigate the effects of irradiation (so far not an issue).

Silicon Sensor Temperatures from DCU Reading



- Module-by-module measurements every 30 s!
- Clearly see regions without direct cooling.
- DCUs read leakage currents, LV, hybrid temperatures as well.

Detector Status: Active Modules



Active, Masked, Not Commissioned

Reasons for Masking

- Control ring **shorts**
- Control rings **missing**
- HV line **shorts**
- HV lines open
- fibres/CCU/...

Active by Partition

TIB/TID	94.63 %
TOB	98.19 %
TEC+	98.81 %
TEC-	99.13 %
Tracker	97.61 %

Almost stable:

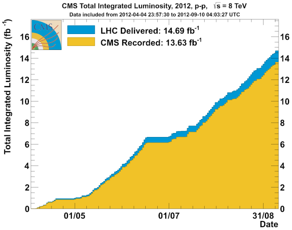
- 2008: 98.5%
- 2011: 97.75 %
- Potentially recoverable in 2013/14 shutdown: 2-3 control rings (0.7-1.0%).

Offline Masking

- Run-by-run analysis of 'express reconstructed' data determines
  - modules temporarily excluded from DAQ,
  - noisy or dead channels, etc.
- Usually flags 0.1-0.6% of channels.
- Results available in delayed (48 h) full reconstruction:

$\Rightarrow$ Tracking knows
  - which hits to ignore (noise),
  - whether a missing hit is expected (dead region).

Strip Tracker Operation



Downtime

- Loss of luminosity delivered by LHC for physics analysis (CMS 2012: 7%).
- Strip tracker doing well: despite large number of FEDs, responsible for only 16% of downtime.

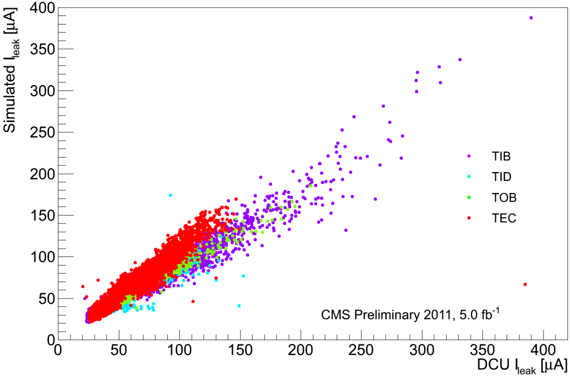
Decrease Downtime by Automation

1. Automatic raising of HV if stable beams:
   - Checking of beam status (from LHC) and radiation monitor.

   $\Rightarrow$ ~1.1 minutes instead of few minutes for manual operation.
2. "Soft error" recovery instead of stop run and reconfigure:
   - Treating single event upset (SEU), broken control rings, etc.

   $\Rightarrow$ Recovery now 20-30 s instead of 2-5 minutes.

Irradiation



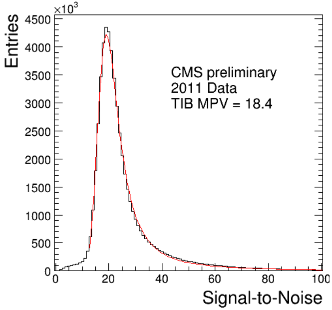
Leakage Currents

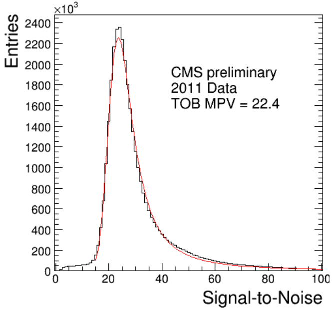
- Increase with radiation damage.

$\Rightarrow$ Give a handle to measure accumulated irradiation.

- Current measured module-by-module via DCU.
- Good agreement after 5 fb^{-1} of integrated luminosity:
  - FLUKA simulation vs measurements.

Excellent Signal-to-Noise Ratio

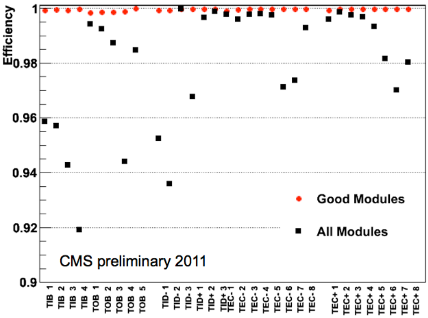




Deconvolution Mode

- Clusters on track only, charge corrected for track angle.
- Distributions nicely follow Landau distributions convoluted with Gaussian resolution.
- Large most probable value (MPV), according to expectations:
  - thin sensors (TIB): ~18
  - thick sensors (TOB): ~22

Hit Efficiencies

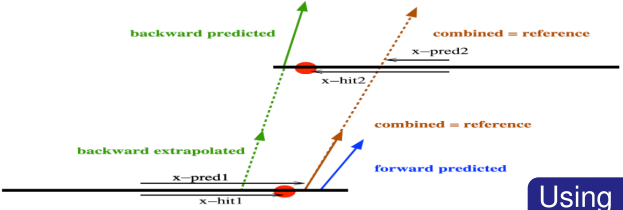


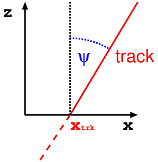
- Measured using good tracks, passing sensors far away from their borders.
- This avoids biases from track pointing uncertainties.
- Not considering last hits on tracks: no result for last layers.

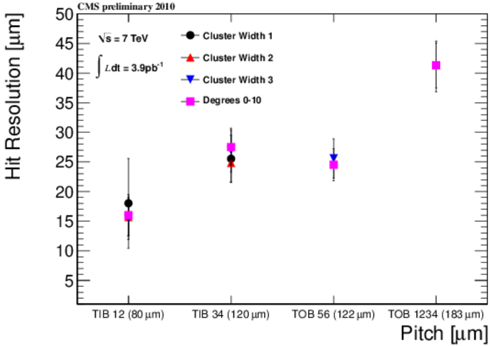
Results

- Considering **All Modules**:
  - variations down to 92%, reflecting bad module distribution.
- For **Good Modules**:
  - all layers $\gg$ 99% efficient,
  - $\Rightarrow$ we know very well which modules are not good.

Hit Resolution Measurements







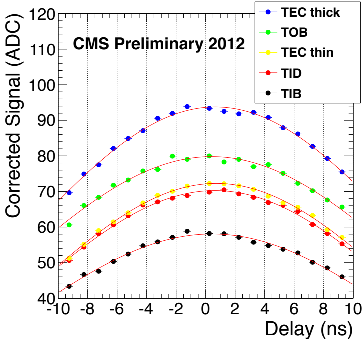
Using Hits in Module Overlaps

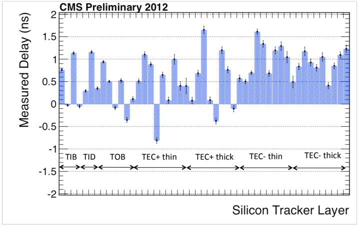
- Track angle $\psi < 10°$.
- Results shown for TIB and TOB layers with pitches:

TIB	L1+2	80 μm
TIB	L3+4	120 μm
TOB	L5+6	122 μm
TOB	L1-4	183 μm

- Values below binary resolutions.

Deconvolution mode data





Timing Check: Few Minutes of Data

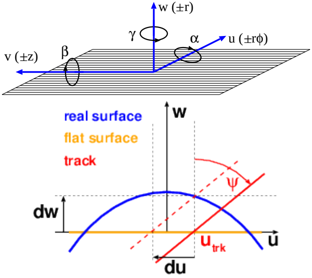
- Time delays in steps of 1.04 ns (i.e. smallest possible adjustment).
- Signal maximum at 0 means current fine timing is perfect.

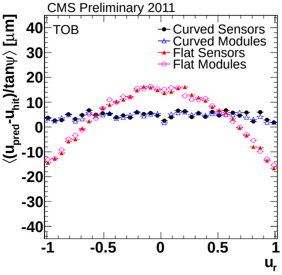
⇒ Largely stable compared to 2011, no adjustments needed.

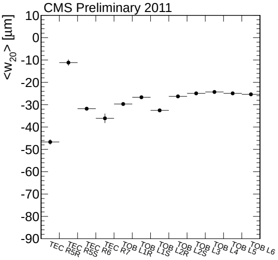
Relevance (Deconvolution Mode)

- If timing off: miss peak of signal, signal-to-noise ratio degraded.
- If far off, efficiency may suffer.
- Even 3 ns can impact alignment (but small effect ⇒).

Alignment: Sensors are Curved

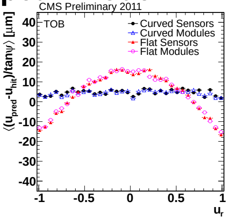




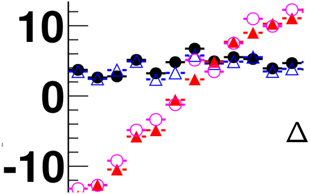


- Single sided silicon processing
  $\Rightarrow$ curved sensors (specifications: $< 100\ \mu$m).
- **Visible** in average track angle corrected residuals
  $\langle \Delta w \rangle = \langle (u_{trk} - u_{hit}) / \tan\psi \rangle$.
- Average amplitude in TOB: -30 μm (with relevant RMS).
- Sensor-by-sensor values determined in alignment:
  hit position corrections let modules **appear flat**
  (as tracking expects).

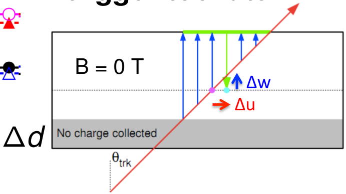
Cosmic ray tracks: peak mode



Zoomed on y-axis



Charge collection: trigger too late



After curvature correction: ~5 μm offset in peak mode data. **Why?**

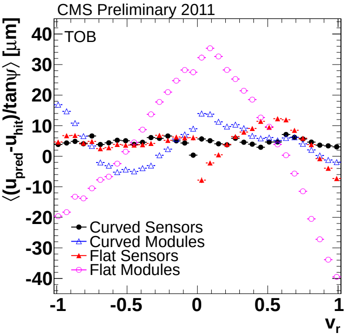
- If timing late: charge of sensor back-plane not collected.

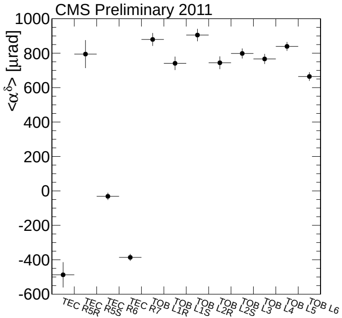
⇒ Sensor appears thinner by Δd, mean shifted by $\Delta w = \Delta d/2$.

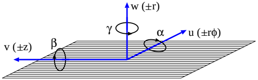
- "Back-plane" corrections for deconvolution data calibrated with 2010 data: $\Delta d = 12\ \mu$m for TOB.
- Improved time alignment in 2011: 3 ± 1 ns in TOB.
- "Back-plane" correction not re-calibrated: tension peak vs deco.
- Alignment dominated by deconvolution mode data.

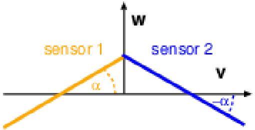
⇒ Offset remains for peak mode data.

Alignment: Double Sensor Modules Have Kinks









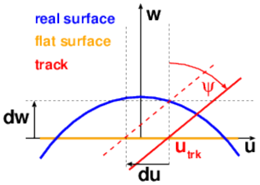
Looking along the Strip Direction

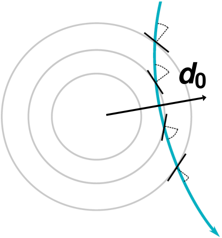
- Modules with daisy-chained sensors exhibit significant kink.

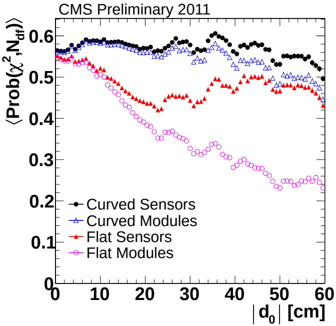
$\Rightarrow$ Alignment treats sensors independently.

- Average kink in TOB: $\langle 2\alpha \rangle = 1.6$ mrad.

Alignment: Modules with Curvatures and Kinks



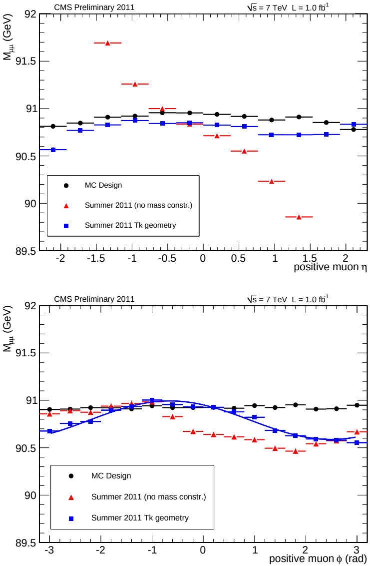




Effect on Track Reconstruction

- Position corrections now applied in hit reconstruction.
- Hits of tracks with large on module surface are most affected.
- Pixel layer 1 for forward tracks $|\eta| > 2$ (not the topic here).
- Cosmic ray tracks:
  - average track fit probability vs d_0 now almost flat.
- Relevance for overall tracking:
  - importance of cosmic ray tracks for alignment (weak modes).

Alignment: Weak Modes and Momentum Scale



Track-Based Alignment

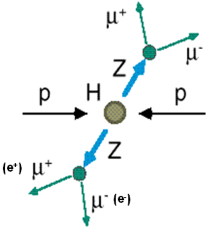
- Common linearised χ^2 fit of alignment parameters (200 k) and ~20 M tracks (MILLEPEDE II).
- Weak modes: χ^2 compensation between geometrical distortions and track parameter biases.
- Here visible in reconstructed $Z^0 \rightarrow \mu^+\mu^-$ mass as a function of direction of μ^+.
- Adding information of nominal Z^0 mass in alignment fit control η dependence (**blue curve**).
- Azimuthal dependence still present, but small.

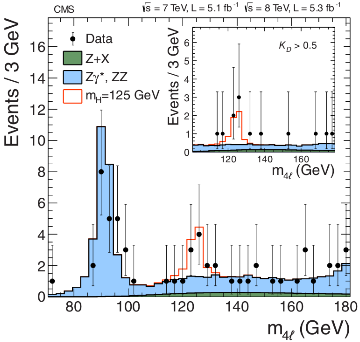
Summary

- CMS silicon strip tracker:
  - analog readout via optical fibres,
  - two readout modes: peak and deconvolution.
- Services work reliably in third year of full LHC running.
- More automated operation to further reduce downtime.
- Irradiation effects follow expectations.
- Good performance:
  - excellent signal-to-noise and efficiency,
  - resolution better than binary.
- Single sided silicon processing introduced sensor curvatures:
  - determined by track-based alignment.
- Alignment largely controls momentum biases from weak modes.

CMS Silicon Strip Tracker

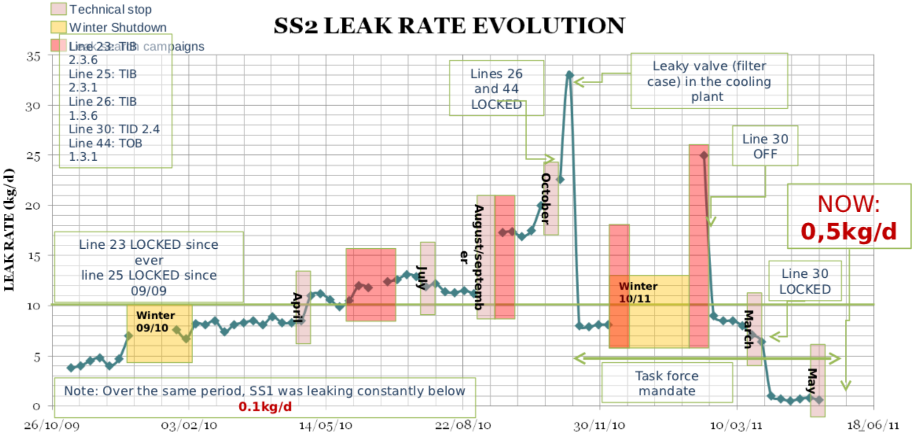
Serving well for physics discoveries.



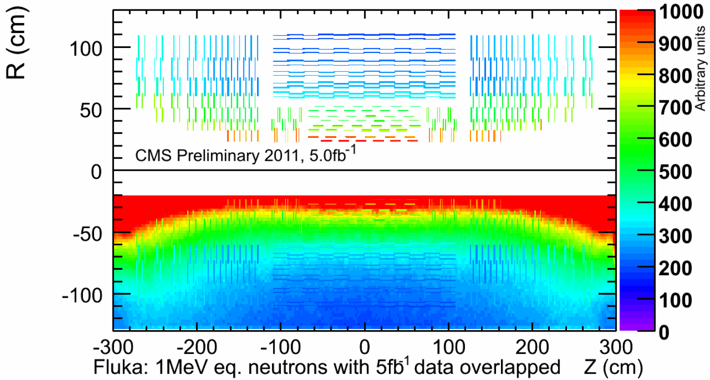


BACKUP

Cooling Leak Rate History



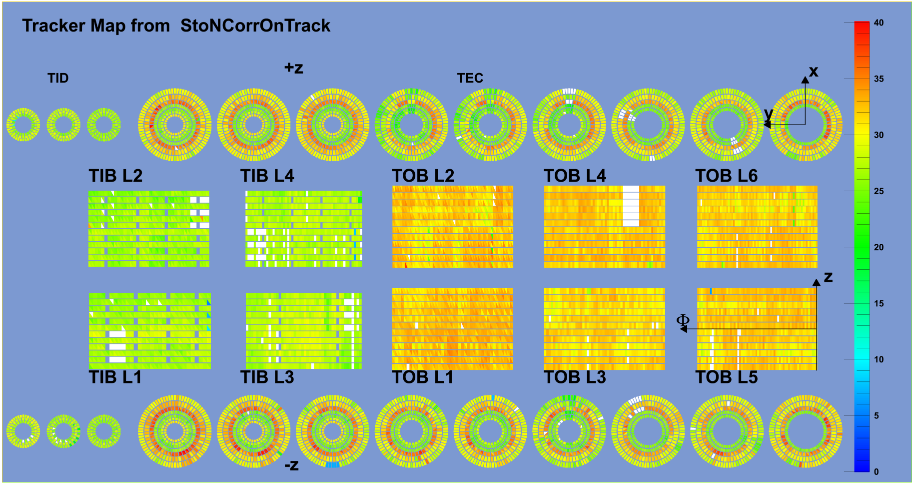
Irradiation



- Normalise leakage current to temperature and volume.
- Compare 1 MeV neutron equivalent.
- Dose per module (upper half).
- Overlayed with simulation (lower half - continuous in space).

⇒ Modules almost vanish, i.e. good description.

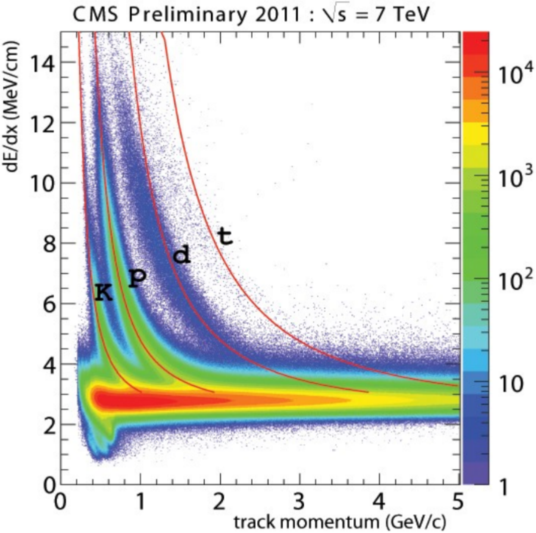
Excellent Signal-to-Noise Ratio



Module-by-Module: Mean Values (> MPV)

⇒ Thin sensors: mean ≈ 25.

⇒ Thick sensors: mean ≈ 35.



CMS Preliminary 2011 : $\sqrt{s}$ = 7 TeV
dE/dx (MeV/cm)
track momentum (GeV/c)
K
p
d
t
0
2
4
6
8
10
12
14
1
2
3
4
5
1
10
10^2
10^3
10^4