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CMS Tracker Layout Studies for HL-LHC

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Abstract

Major LHC upgrades planned around 2020 are expected to increase the delivered instantaneous luminosity above $10^{34} \text{cm}^{-2} \text{s}^{-1}$ while keeping the bunch spacing at 25 ns, or even increasing it. In order to cope with the higher pile-up, the CMS collaboration is planning to build a completely new tracking system, which will probably implement also trigger capabilities. In order to identify the best possible design, a tool was developed (tkLayout) to generate layouts, make an estimate of the material budget and even provide an a priori estimate of the tracking performance. tkLayout can be used to optimize a given layout concept, or to compare the performance of different approaches. tkLayout is not specific to CMS, thus it can be used to design upgrades for other experiments. The technology of tkLayout is presented and results for several layout designs discussed.

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1. Overview

The Silicon Strip Tracker currently operating in CMS \cite{1} is the largest detector of its kind ever built. It is 5.6 m long (in the beam direction, $z$) with a diameter of 2.2 m. With its 10 barrel layers and 12 disks per side, it features 200 m$^2$ of sensitive surface in 15 148 modules with $9.3 \times 10^6$ channels read out through 36 392 analogue optical links. The Large Hadron Collider (LHC) project is currently in its first phase of physics exploitation with a center-of-mass collision energy of 7 TeV (half of the nominal value) and a record peak instantaneous luminosity of $3.6 \times 10^{33} \text{cm}^{-2} \text{s}^{-1}$ (one third of the nominal value). The performance of the LHC in delivering luminosity to the experiments is continuously growing.
According to current plans the nominal luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$ and center-of-mass energy of 14 TeV should be reached after an upgrade of part of the accelerator, scheduled for the first “long shutdown” of the LHC in 2013-2014. Two further long shutdowns are planned for the late 2010s and early 2020s to allow various upgrades after which the instantaneous luminosity delivered should exceed the design goal, eventually reaching a peak luminosity of $5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ that will be sustained for a large fraction of each fill, through luminosity leveling. This scenario is known as High-Luminosity LHC (HL-LHC, Table 1).

In this scenario the CMS tracker will have to provide tracking in a more challenging environment. The basic requirements can be summarized as follows:

- Robust tracking in operation with up to 200 collisions per bunch crossing in the worst-case scenario of 20 MHz operation (to be compared to the original LHC design figure of 20 collisions per crossing); this can be achieved by maintaining the occupancy at the level of a few percent, which requires increased granularity

- Ability to provide satisfactory performance up to an integrated luminosity of approximately 3000 fb$^{-1}$, to be compared with the original figure of 500 fb$^{-1}$; this requires the selection of more radiation hard silicon sensor material, especially for the innermost regions (up to $10^{15}$ n$_{eq}$ cm$^{-2}$ at 20 cm [2]), as well as more stringent criteria in the qualification of electronics and mechanical assemblies.

- Reduced material in the tracking volume; the material is the most severe limitation on the performance of the present tracker [3], and it is dominated by electronics and services (notably in the region between barrel and end-cap).

To cope with this requirement the only viable option is to replace the current tracking system with a new detector.

The event filtering at Level-1 also becomes substantially more challenging at high luminosity, not only because the rate of events passing a given selection scales with the instantaneous luminosity, but also because the performance of selection algorithms degrades with increasing pile-up. For example, the single muon Level-1 rate has an irreducible tail due to poorly measured tracks that are compatible with straight trajectories, and are therefore not removed even by increasing the $p_T$ threshold: such an effect is aggravated at high luminosity by accidental coincidences. Currently in the High-Level Trigger, where the information from the tracker is also added, the reconstruction is substantially improved and the rate of muon candidates follows closely the generator rate. Upgrades to the trigger system are planned (e.g. including the fourth RPC and CSC stations, now under construction, will allow to request 3 out of 4 points for a muon candidate), which will yield an acceptable rate for luminosities up to $2 \times 10^{34}$ cm$^{-2}$ s$^{-1}$, but the rate will saturate again the available quota for higher luminosities (see also Figure 1). Hence the collaboration is studying the option of using tracking information in the Level-1 selection, along the lines of what is done today in the HLT.

One possibility would be to instrument the upgraded tracker with detector modules capable of measuring a track transverse momentum ($p_T$) locally and sending high-$p_T$ hits to a real-time tracking processor.
embedded in the Level-1 trigger. This option was demonstrated to significantly improve the Level-1 event selection [4, 5].

Implementing the ability for the tracker to contribute to the Level-1 trigger is likely to increase the material amount in the tracking volume, which is already a limiting factor for performance of the current tracker. This fact poses a key question in the design of the upgraded detector: what is the impact of different design choices on the final detector performance?

2. A detector layout design software

When designing a new detector for high energy physics it is common practice to rely on detailed (and complex) Monte Carlo simulations. While this cannot be avoided for the qualification of a detector design, this approach needs a lot of effort to understand simulation details and to optimize event reconstruction algorithms.

For this reason a software tool (tkLayout) was developed to evaluate the potential performance of a design by making a simple error estimate from first principles.

tkLayout automatically creates a description of the layout geometry with the material amount implied from a small set of design parameters, as described in [6]. This is used to produce summary reports on the layout (number of modules, total silicon surface, etc.) and to estimate the potential resolution in track reconstruction.

2.1. Resolution estimate

The method used by tkLayout is based on the computation of the error propagation in the fitting procedure, taking into account the precision of the measurement points and multiple scattering. This is done by considering two distinct fits: a circle in the \((r, \phi)\) plane and a straight line in the \((r, z)\) plane. In reality these are not independent, but this approximation was proven to be valid, \emph{a posteriori}, by a comparison of the results derived with a full simulation of the CMS Silicon Strip Tracker.

The particle multiple scattering can be considered a deviation from the ideal track to be measured, and thus it can be treated as a measurement error. Hence, the measurement point covariance matrix \(C\) can be written as \(C = C^M + C^R\), with \(C^M\) the covariance matrix due to multiple scattering and \((C^R)_{ij} = \delta_{ij}\sigma_j\) the covariance matrix due to the intrinsic resolution of the measurement point \(P_i\), which is taken as an input by tkLayout.
If we assume that the Coulomb multiple scattering probability density can be calculated from the radiation length of the crossed material [7], and has a finite variance and that scattering angles $\theta$ are small ($\sin(\theta) \approx \theta$), then matrix elements $(C^M)_{ij}$ can be computed for any particle trajectory with a simple algorithm depending only on the radial position $r_i$ and composition of the surfaces crossed by a charged track and the charge and momentum of the track:

$$C_{mn} \approx \sum_{i=1}^{n<m} (r_m - r_i)(r_n - r_i) \langle \theta_i^2 \rangle$$  \hspace{1cm} (1)

Once the measurement point errors are known, the error on the fit of track parameters can be obtained. The computation for the fit in the transverse plane $(r, \varphi)$ provides an estimate of the resolution of track’s transverse momentum ($p_T$), transverse impact parameter ($d_0$), and track azimuthal direction at the origin ($\varphi_0$). The computation for the longitudinal plane $(r, z)$ provides the expected resolution of longitudinal impact parameter ($z_0$) and track polar angle ($\theta$).

tkLayout then proceeds by selecting a number of sample directions and estimates the expected resolution on the five parameters of the track as a function of the pseudorapidity ($\eta$) and transverse momentum ($p_T$). The former determines which surfaces are crossed by the track while the latter appears in the calculation explicitly (as track bending radius) and implicitly (determines the average scattering angle $\theta$ on the surfaces). To simplify the calculation all tracks are considered to be straight and to start from the origin of the coordinate system (the center of the experiment).

2.2. Material model

A simplified description of the material is used by tkLayout. Every detector module is associated with a set of materials (and corresponding weights) according to an user-defined table. Each material can be identified as “service” (like power cables and cooling lines). In this case an ad-hoc volume is automatically created to represent its routing from the modules to the detecting volume edges (more details can be found in [6]).

3. Model validation

The current CMS Silicon Strip Tracker was used as a benchmark to validate the accuracy estimate performed by tkLayout. The accuracy of this comparison is limited by the fact that tkLayout can only produce a layout similar to that of the outer barrel and outer end-caps of the present CMS tracker, so it fails to correctly model the inner part of the detector and especially the actual routing of services around the inner disks (details on CMS tracker geometry are described in [8]).

A layout was created with tkLayout with the same number of barrel layers and end-cap disks as the CMS Tracker. The material model was tuned in order to reproduce the Outer Barrel material and it was then applied to the whole tracker layout. A smaller tracker was also generated to represent the pixel detector [9]. The correct strip pitch $\pi_i$ was assigned to all of the strip tracker sensors and the resolution $\sigma_{i}^2 = \pi_{i}^2 / 12$ was taken to be that of a binary readout system. The resolution of the pixel detector was instead assigned explicitly to match the actual detector. No further tuning was performed.

The present CMS tracker is accurately simulated in the official software of the collaboration which was validated against the collision data collected. The material amount (measured in radiation lengths) obtained from the full simulation is compared in Figure 2 with the same quantity estimated with tkLayout. The material amount is correctly reproduced at low $\eta$ and at the material peak ($\eta = 1$ to 1.4). The accuracy in measuring $p_T$ of a muon with $p_T = 10 \text{ GeV/c}$ is shown in the same figure. The tkLayout estimate matches closely the full simulation in the $\eta$ range where the material amount is correctly reproduced.

A complete comparison shows that the resolution on the five parameters is correctly reproduced by tkLayout with an error of 10% to 20% even in the rough approximation described above [6].
4. Models of detector modules

Three types of modules were described within tkLayout, all built with two planar sensors: the first one, named "stereo" is equivalent to the double-sided detector module currently installed in CMS (Figure 3, left), while the other two, named "pT-2S" and "pT-PS" provide a local measurement of the track transverse momentum (Figure 3 center and right respectively).

4.1. Stereo module

The detector is made by a sandwich of two strip sensors placed parallel to each other with a small gap (typically 1 mm). Each sensor is 9.2 cm × 9.2 cm wide and has 1024 strips, with a pitch of 90 μm. The strips of one sensor are aligned along the local y coordinate of the module (i.e. parallel to the beam axis for barrel modules and pointing towards the beam axis for end-cap modules), while the other sensor’s strips are tilted by an angle of 100 mrad. Each sensor is read out by front-end chips mounted on two hybrids which are placed on top of the sensor itself: this way four arrays of short strips can be designed on the sensor (4 strips of 2.3 cm can fit along the local y coordinate).

When a Level-1 Trigger is received, data from all the strips are read out. During event reconstruction the correlation between hits in the two sensors provides a measurement of the local y coordinate of the hit.

Readout and control of the front-end electronics is demanded to optical links between GigaBit Transceivers (GBTs) [10] in the counting room and GBTs on the outer surface of the tracker section (i.e. the end-flange of...
the barrel and the outer cylinder of the end-cap). The latter are connected to the modules via micro-twisted pairs up to the end-flange of the barrel.

Given the high segmentation (2.3 cm-long strips) this detector module is suitable for the inner part of the detector, where the density of tracks is higher. The local \( y \) measurement precision (260 \( \mu \)m) is determined by the strip pitch and the stereo angle.

4.2. \( pT \)-2S module

In this module the strips of the two sensors are parallel to each other and the front-end electronics must read out the two sensors at the same time and perform a hit correlation. The local \( x \) coordinate of the hits measures the charged particle trajectory perpendicular to the solenoidal magnetic field \( B \), and thus the distance \( \Delta x \) between matching hits in the two sensors is function of the particle \( pT \):

\[
(\Delta x)_{\text{BARREL}} = \frac{d}{\sqrt{a^2 - 1}} \quad (\Delta x)_{\text{ENDCAP}} = \frac{d}{\sqrt{a^2 - 1}} \frac{r}{z} \quad a = \frac{2pT}{0.3 B r \text{ GeV/c}}
\]

with \( d \) distance between the two sensors and \( r, z \) cylindrical coordinates of the module. Closely matching hits (\( \Delta x < \Delta x_{\text{cut}} \)) belong to high-\( pT \) tracks and are sent through an integrated GBT to be used in the Level-1 trigger.

To have a good \( pT \) discrimination \( \Delta x_{\text{cut}} \) must be much bigger than the strip pitch \( \pi \), which is typically 100 \( \mu \)m. For the CMS magnetic field \( B = 3.8 \text{T} \) and a \( pT \) cut at 1 GeV/c, the optimal distance between the sensors in the CMS tracker region varies between 0.8 mm (barrel, \( r > 50 \text{ cm} \)) and 4 mm (end-cap, \( r \approx 25 \text{ cm} \)).

When a trigger is received by the module, the complete information of the event is transferred to the standard DAQ system. In order to read out strips from both sensors the hybrids must be placed at the edge of the module, and this limits the strip length to half of the module size (approximately 5 cm).

For each event, \( f \) fake high-\( pT \) hits will be found from the combination of uncorrelated low-\( pT \) hits. If \( N \) is the number of strips per sensor and \( H \) is the average number of hits per event on each sensor, \( h = H/N \) is called hit occupancy, and

\[
f = h^2 N \frac{2\Delta x}{\pi}
\]

In order to keep the combinatorial background below 0.1 fake matches per event on a sensor with 1024 strips and a search window of 5 strips, the hit occupancy must be lower than 0.5\%. This limits the use of 5 cm-long strips to the region at \( r > 50 \text{ cm} \) in the scenario with 100 pile-up events per bunch crossing.

This module measures \( r_\phi \) with a precision of \( \sim \pi/\sqrt{6} \), but it does not provide a direct measurement of the local \( y \) coordinate.

4.3. \( pT \)-PS module

In order to overcome the limitations of the \( pT \)-2S module, a variant was designed with one of the two sensors being a pixel detector. This way the \( y \) coordinate of the hit can be measured locally, and is also available for the track reconstruction in the Level-1 Trigger. In the design considered here the hit correlation is integrated in the pixel read-out chip and the connectivity with the strip sensor is implemented through hybrids at the sides of the module. These modules are intended to cover the inner part of the detector, thus a strip length of approximately 2 cm is needed, limiting the size of the sensor to 10 cm \( \times \) 4 cm. The minimum pixel pitch achievable with standard industrial bump-bonding techniques of 100 \( \mu \)m was chosen for the strips and pixels. The local \( y \) measurement precision (380 \( \mu \)m) is determined by the longitudinal size of the pixel (1.3 mm).

5. Layout comparison

One of the studies performed with tkLayout using these modules is reported here. Two layouts with different features were compared; the first is made of strip sensors only (layout \( S \)) and the second (layout \( P \)) is built with \( pT \)-2S (strip) and \( pT \)-PS (pixel) modules (both layouts are sketched in Figure 4).
In both layouts end-caps are built with rectangular-shaped modules, as in the barrel. The other possibility is using wedge-shaped sensors with radial strips, which is the natural choice, as the hit strip gives a direct measurement of the \( \varphi \) coordinate and the wedge shape optimizes the use of detecting surface over the disk. However this choice requires a different geometry for each ring of end-cap modules, which implies considerable additional cost in production and potential logistic problems. The use of rectangular modules in the end-cap was evaluated with tkLayout and the loss of accuracy was deemed to be negligible, while the increase of modules needed was estimated to be only 4%.

![Fig. 4](image)

**Fig. 4.** Sketch view of 1/4 of the layouts discussed here, in the \( r, z \) projection: layout S on the left and layout P on the right. Each line represents a detector module. Light gray lines represent stereo modules, dark gray lines represent pT-PS modules and black lines represent pT-2S modules.

### 5.1. Layout S

This detector layout is built only with strip sensors, a conservative design that relies on a module structure not far from the present tracker and allows a strip pitch of 90 \( \mu \)m in all the modules.

The higher density of tracks in the inner part \( (r < 500 \text{ mm}) \) is managed using short strip detectors (stereo). These also provide a good resolution along the local \( y \) direction of the module, which is needed to project the tracks back to the pixel detector. This measurement also increases the resolution in \( \cot(\theta) \), which is important in the forward region: the end-cap modules measure the coordinate set \( (\varphi, z) \), while the coordinate set needed to measure \( p_T \) is \( (\varphi, r) \). In order to estimate \( r \) in end-cap modules \( \cot(\theta) \) must be precisely measured. In the outer region trigger modules are used (pT-2S), so that a simple tracking trigger can be built.

It should be noted that no local \( y \) information is provided to the Level-1 Trigger in this design.

### 5.2. Layout P

To overcome this problem another layout was designed, with pT-PS modules in the inner part in place of the stereo modules. The pT-PS modules provide the local \( y \) measurement in the standard readout like the stereo module, but this information is also available to the Level-1 Trigger. A good measurement of this coordinate is needed in order to reconstruct \( z_0 \) (the longitudinal impact parameter). This can be used to associate the tracks to different pile-up events, which is important in the high pile-up environment of HL-LHC. At least two layers of pT-PS modules are needed to extrapolate the track to the beam axis, so in order to provide redundancy to this measurement, the third barrel layer and the corresponding end-cap rings were populated with pT-PS modules.

The measurement of the local \( y \) coordinate in the inner layers improves the resolution on \( \cot(\theta) \). Having this measurement available in the Level-1 trigger processor impacts the resolution on \( r \) (and thus of \( p_T \)) for tracks in the end-cap.

The price to pay for this additional feature is a heavier module (circa 1.1 g per cm\(^2\) of sensing surface in place of 0.7 g for the stereo module), which will degrade the tracking resolution because of the multiple scattering.
5.3. Performance comparison

A quantitative comparison of the expected performance of these two layouts was performed using tkLayout. A summary of the interesting parameters is shown in Figure 5. The studied quantities related to standard tracking were computed for 100 possible track directions, and then averaged over three regions of pseudorapidity: central (0 < η < 0.8), intermediate (0.8 < η < 1.6) and forward (1.6 < η < 2.4) of equal Δη = 0.8. The first parameter studied is the pair production probability of a high-energy photon inside the tracker. This is directly related to the total material amount measured in radiation lengths and shown in the top-left histogram of Figure 5. The increase in material due to the heavier pT-PS modules is visible, but not dramatic. The momentum resolution (σ(p)) on muons with pT = 10 GeV (shown in the top-center histogram) and pT = 100 GeV (top-right) are similar between the two layouts.

The layout characterization was repeated considering only the information from pT-measuring modules and adding a constraint on the impact parameter: z0 is limited by the length of the luminous region (σ(z0) = 7 cm), while d0 was constrained to σ(d0) = 3 mm. Any track falling out of these constraints will be reconstructed with a worse resolution than that reported here. The constraint on d0 was chosen to be wide enough to contain tracks from displaced secondary vertices from b-meson decays.

This method gives an evaluation of the resolution achievable with a hypothetical Level-1 Tracking. The studied parameters were averaged over shorter η regions (Δη = 0.7) to analyze the coverage for the trigger up to η = 2.1.

The achievable resolution on the track z at the origin (shown in the bottom-left histogram of Figure 5) is 1 mm or better in all the regions for layout P, that is 35 to 50 times better than layout S, thanks to the local y resolution being available in the Level-1 Trigger. The expected length of the luminous region is 16 cm FWHM and thus the identification of the track z0 with a precision of 0.1 cm is compatible with a scenario with a pile-up of 100.

The achievable resolution in the measurement of pT for muons with pT = 10 GeV and 100 GeV in the Level-1 Trigger is shown in the bottom-center and bottom-right histograms, respectively. Here the performance of layout P is better over the whole range, especially in the intermediate and forward regions (0.7 < η < 2.1) due to a more extended coverage of the tracking volume and also because in these regions most of the measurement points come from end-cap modules and layout S is missing a precision measurement of the track θ in the trigger.
6. Conclusions

A generic analytic method to evaluate the accuracy of a tracking device was derived. This allows to compute the full covariance matrix of the track parameters for any configuration of the detector with respect to the track. A software tool (tkLayout) was developed, capable of describing a tracker detector geometry from a small set of basic parameters. A model of the material budget was also implemented, which allows to describe detector materials and automatically takes into account the service routing in the tracking volume. tkLayout also implements the mentioned estimate of tracking accuracy and it was validated against a full simulation of the CMS tracker. The accuracy of tkLayout in reproducing the performance of the present tracker was proven to be 10% to 20% and it is expected to be better than that for the layouts proposed for the upgrades.

This software is currently used within CMS to evaluate possible tracker layout concepts, and comparing different design approaches. One of those studies was presented here, comparing two alternative layout designs (named S and P) embedding $p_T$-measuring modules that can contribute to the Level-1 Trigger.

Layout S is completely populated with micro-strip detectors: $p_T$-modules in the outer part only and “traditional” stereo modules in the inner part. Layout P instead has strip modules in the outer part and pixel-strip mixed modules in the inner part, all of them $p_T$-measuring.

Layout P was proven to be similar to Layout S in tracking performance, even though it has more material and worse $r\phi$ resolution

On the other side Layout P was shown to have a greater potential than Layout S in resolving the track transverse momentum in the forward region (5 to 10 times better for $1.4 < \eta < 2.1$) and also in resolving $z_0$ on the whole studied range (35 to 50 times better for $\eta < 2.1$), with an expected error of $\sigma(z_0) < 1$ mm.

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