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CMS Tracker Endcap geometry description in simulation

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Abstract

The success of the CMS physics programme relies on a reliable prediction for track measurements. In track reconstruction the position, orientation and strip topology of the active detector elements as well as the material budget is used to estimate the hit position and uncertainties due to intrinsic detector resolution and multiple scattering, respectively.

We describe the implementation of the CMS Tracker end-cap geometry, document the general approach including approximations, and explain the validation procedure.

Sensors are positioned with an accuracy better than 15 μm with respect to engineering drawings, and the overall TEC weight from simulation corresponds to the true weight within 1.5%, with an estimated systematic uncertainty of 3%.

1 Introduction

In the CMS [1] physics programme [2], track measurements are indispensable for top-physics, b-physics, electron/photon identification and many other studies. A detailed description of the active and passive materials is essential for correct estimates of hit positions, hit uncertainties and multiple scattering estimates, which are necessary ingredients for reliable track parameters.

The CMS tracker [3] consists of several sub-detectors, including two cylindrical end-caps with radius of $1135.1\,\mathrm{mm}$, starting at $|z| = 1240\,\mathrm{mm}$ and extending up to $|z| = 2832.4\,\mathrm{mm}$ (cf. Figure 1). These two end-caps are named TEC+ and TEC-, the sign indicating the sign of the global z-coordinate. Together they contain 42% of the silicon strip tracker modules and therefore form the largest subdetector.

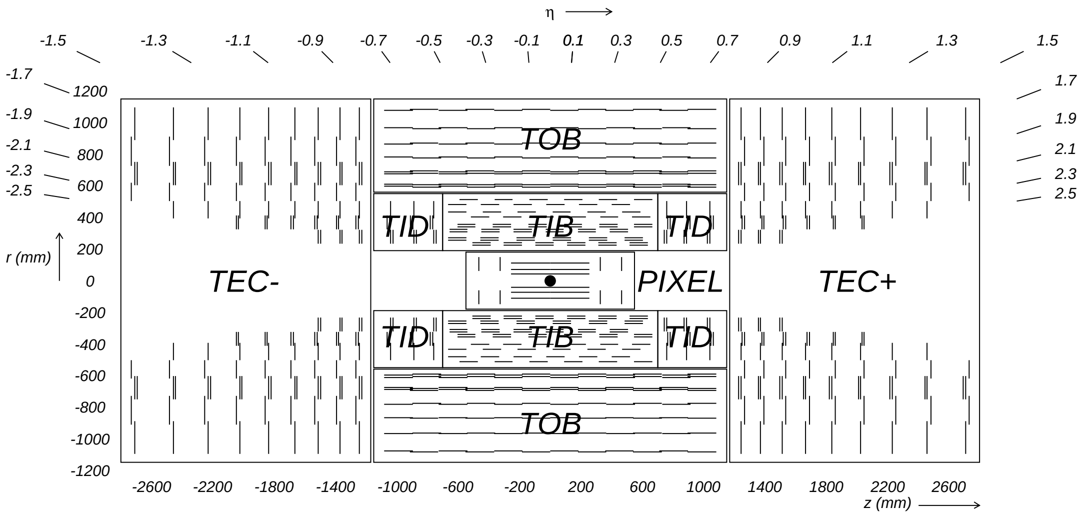

Figure 1: Schematic layout of the CMS Tracker. The pixel systems are placed closest to the interaction point, surrounded by the strip detectors. The pixel barrel, the Tracker Inner Barrel (TIB) and Tracker Outer Barrel (TOB) form concentric cylinders around the interaction region, whereas the pixel endcaps, Tracker Inner Discs (TID) and Tracker End Caps (TEC) close the barrel parts, providing measurements up to $\eta = 2.5$.

2 The Tracker Endcaps

The two TECs were built in an identical way. Due to construction tolerances, small differences between the two TECs exist in reality, which become manifest in a weight difference of 4.3 kg between the weight of 734.4 kg for TEC+ and 730.1 kg for TEC-. Since this difference is with 6‰ very small, TEC+ and TEC- share the same geometry description in simulation and reconstruction.

2.1 TEC structure

Each TEC consists of eleven disks, with the beam passing a hole in the center of the disk. Each disk is made of a NOMEX honeycomb structure stabilized by two carbon fibre compound plates. The first and last disks close and insulate the detector volume. The nine central disks (designated by numbers from one to nine) carry the active detector elements. The left part of Fig. 2 shows disk one. Holes in the disks reduce the material budget.

On each disk, 16 petals are mounted. A petal covers a narrow ϕ region and is also build from a NOMEX core and two carbon fibre skins. To ensure hermeticity in ϕ, petals are mounted alternating on the front and back side of a disk, providing overlap. Petals carry up to 28 modules which are arranged in up to seven arcs, overlapping in r. A cooling pipe is placed inside the NOMEX core, and on the skins electronic boards carrying integrated circuits provide clock, power and signal lines to the modules. The modules are mounted on aluminium inserts which are connected to the cooling pipes in order to extract the heat generated by the front-end electronics. The modules consist of a carbon fibre compound or graphite frame supporting the silicon sensors and the front-end hybrid.

On the outer edge of the disks, eight carbon fibre compound bars provide structural integrity of the TEC. Inside the u-shaped profile of the bars optical fibres carrying the read-out data are routed. Alongside each of these so-called

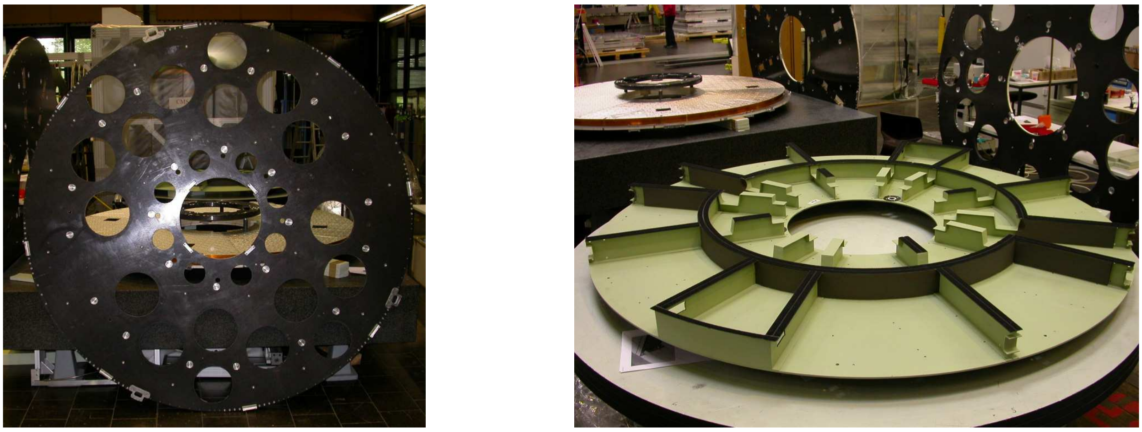

Figure 2: TEC disks in the Aachen workshop. Left: Fully assembled TEC disk 1. Right: TEC bulkhead (bottom) and back disk (top left) with mounted alignment ring.

service channels four steel pipes provide coolant to the petals. The aluminium power and control cables surround the cooling pipes (see Fig. 3), branching to the petals. The TEC is connected to the services at its back side. Onto the last disk, the bulkhead (see right hand side of Fig. 2) is attached. All cables and optical lines are routed to connectors on the bulkhead. Connected to the back, disk an alignment ring carries tiltmeters and laser diodes, the latter pointing to the muon system.

A thin cylindrical carbon fibre skin mounted at the outer perimeter of the TEC closes the TEC volume. The TEC is held in place inside the support tube by four solid carbon fibre compound rails.

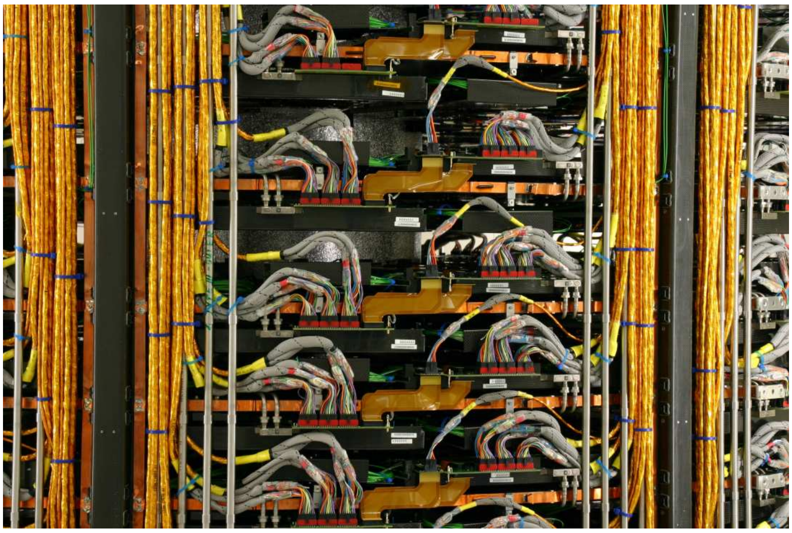

Figure 3: TEC services for one TEC sector: Cables are arranged around and run along the cooling pipes until they branch to the front petals (left half) or back petals (right half). The five horizontal structures are disks carrying the petals. Inside the service channels (vertical black structures to the left and right) run the optical fibres.

2.2 Tools for software representation

The geometry description is part of the CMS software framework (CMSSW) [5]. It harnesses the GEANT4 [6] program for the simulation of particles passing through the detector. To this end, detector components are represented by simplified volumes. The description of these volumes, their placement and the material properties are stored in XML files which follow the Detector Description Language (DDL) [7]. The DDL allows to call algorithms written in the C++ [8] language for repeated placement of similar volumes, e.g. of the TEC modules.

3 Software representation

In order to simulate the detector efficiently, GEANT4 allows to structure the geometry description hierarchically. Typically sub-assemblies of the TECs are used as a mother volume for all parts this sub-assembly consists of. As one example, the “TECDisk” mother volumes contain the disk structure, the disk inserts, most supporting elements and the petals. Some of these daughter volumes are mother volumes by themselves, as for example the petal. The lowest level of this hierarchy are the modules. There, the active silicon, the electronic components and the supporting structures are contained in the “TECModule” mother volume. The mother of all volumes describing the TEC geometry is the “TEC” volume. While this hierarchical structure is useful to optimise both speed of simulation and development it introduces a fundamental problem of the geometry description: Since a child volume has to be fully contained in its mother, all structures that in reality connect parts of the detector can not be easily simulated by a single volume. This includes all wires, pipes, bolts and other supporting structures.

3.1 Overview of the simulated hierarchy

In this section we give a general overview of the most prominent volumes in the software representation of the tracker end cap, including their hierarchy[1)].

The highest level in the hierarchy and mother to all other volumes of the tracker end-cap is the “TEC” volume. It contains larger substructures like the “TECWheels” and the “TECServices”. The “TECWheels” volume is used to describe different types of wheels (“TECWheel”) and contains the actual supporting structure (“TECDisk”) as well as the container of the front and back petals (“TECPetalCont”). Besides of containing the supporting structure (“TECPetal”) the petal container is mother to a volume containing the electronic parts (“TECICBCont”) and volumes containing several module mother volumes (“TECRing”). The rings finally contain the module mother volumes (“TECModule”) and the bridges which cool and support the modules.

The “TECServices” volume describes the services. It contains everything that has a radial position larger than $1103\,\mathrm{mm}$. This includes both high voltage and low voltage cables (“TECCable” and “TECPhiCable”), cooling and gas pipes (“TECCoolPipe” and “TECGasPipe”) and the optical fibres together with their supporting structure (“TECServChannel”).

The bulkhead is simulated in a volume outside of the TEC mother volume (“TrackerBulkhead”). It is divided into structural components (“BHDisk”, “BHCovers”), the cable connections (“PIXPatchpanel” and “TECPatchpanel”) and the alignment ring (“TECAlignRing”). Additionally the bulkhead contains a volume which simulates all cables, pipes and fittings connecting the TEC to the Bulkhead (“OuterCables”).

3.2 General rules

The modelling of the TEC geometry software description followed a few empirical guidelines, which were agreed upon by the tracker geometry developers.

- Combine small parts in a single volume using the smearing method (see section 3.2.1 below).
- Use increased details for metallic parts.
- The closer volumes are placed to the active silicon areas, the higher the detail level of the description.

These rules are designed to produce an accurate simulation of the detector, while keeping the number of simulated volumes as small as possible. This is the key to an efficient usage of computing resources during the Monte Carlo simulation of the TECs.

3.2.1 Material Smearing

According to the guidelines outlined above, often several real world parts had to be described in the software by a single volume. As one example, the integrated circuits, power lines, connectors etc. of the petal electronics were smeared above the full area of the electronic boards.

[1)] The names of the structures are given as in the software representation, but in order to keep this section comprehensive any numbers or letters specifying different types of the same sort of volumes are omitted. A complete list of all volumes can be obtained from the IGUANA visualization.

In a first step, the masses $m_i = \rho_i V_i$ $(i = 1...n)$ and materials of the components had to be determined. Then, their relative fractions f_i were computed and a mixture generated according to the formula

$$f_i = \frac{m_i}{\sum_{j=1}^{n} m_j}. \tag{1}$$

Since the simulated volume V_{sim} and the real volume $V_{real} = \sum_i V_i$ can be different due to approximations and hierarchy constraints, the density of the smeared volumes had to be adjusted by a scale factor

$$s = \frac{V^*_{real}}{V_{sim}}. \tag{2}$$

Materials used in the smearing process ("basic" materials) were both elementary (like Cu, Al, C) and compounds (e.g. PEEK (Poly-Ether-Ether-Ketone) or CFC (carbon fibre compound). To keep the list of basic materials used for the smearing manageable, materials which differed only slightly in density or fractions of constituents were approximated by the same basic material. To compensate for the different densities, the volume V^*_{real} was calculated by

$$V^*_{real} = \frac{\rho_{real}}{\rho_{basic}} V_{real} = \frac{m_{real}}{\rho_{basic}}. \tag{3}$$

In order to ease the calculation, a custom program named `mixture.f` [9] was used.

3.2.2 Geometric Approximations

Although it is in principle possible to produce objects of any shape in DDL using polyhedrae and Boolean volumes, for simplicity most of the objects and mother volumes in the TEC detector description are simulated using three simple shapes: boxes, trapezoids and tubs. Trapezoids are three dimensional extrusions of trapezoidal shapes, which can be tilted in two angles (Figure 4 left). Boxes are special cases of trapezoids (Figure 4 middle). These two are well suited for most electronic components, support structures and the sensors. In many cases the real shape can be well approximated by introducing a box or trapezoid, because at least one dimension of the real volume coincides with the simulated one. For the other dimensions the fractions of the real object inside and outside of the simulated volume where minimised. This was achieved by adjusting the remaining dimension to keep the volume in the simulation and reality equal. For example the horizontal dimension of the circuit board carrying the front end electronics ("TECHybrid") was identified as such an dimension. On the left hand side of Figure 5 the outcome of the above procedure is sketched.

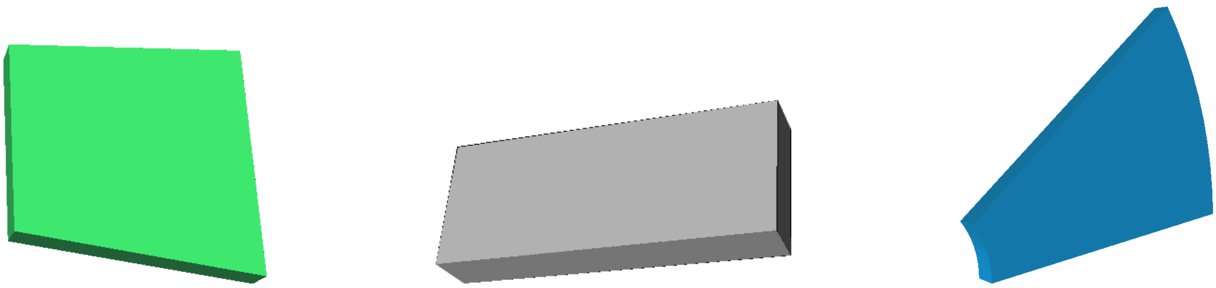

Figure 4: Most frequently used GEANT shapes in the description of the Tracker endcaps. Left: Trapezoid; middle: Box; right: Tub.

Tubs (Fig. 4 right) are extruded slices of rings. On the one hand they are used to describe any bolts and pipes and on the other hand they are used for volumes mounted in a ϕ-symmetric manner (like the petal bodies or the rings). Metallic fixations for these parts, which one would like to model with high accuracy, are mostly at the edges of big ϕ- symmetric structures (e.g. the disks). The real shape of the fixations could be approximated with high accuracy by boxes or trapezoids. This, however, would inevitably cause overlaps with the rounded edges of the tub mother volumes (Fig. 5 right), which have to be averted by using tubs for those volumes as well (i.e. TECFixSupport).

A different type of approximation was necessary in those places where the exact shape and position of the object was not known precisely. Typically this happened for flexible parts which were bent and whose position got adjusted during the TEC assembly process. A typical example are the cables at the outer radius of the TEC, cf. Figure 3. In these cases the simulated volume will encompass the region in which the objects reside. Naturally the simulated material density used for those volumes is much smaller then the density of the actual object.

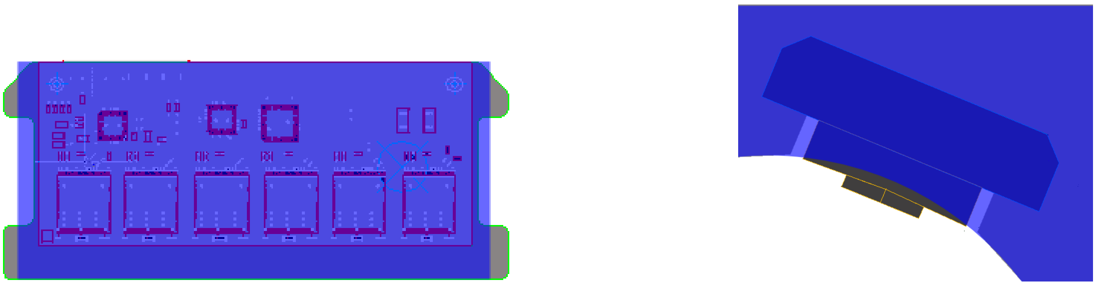

Figure 5: Examples for geometrical approximations. Left: TECHybrid is modelled by a box, keeping the overall volume constant. Right: TECFixSupport modelled as a box overlaps with the mothervolume which is a tub.

3.3 Relations to other parts of the tracker

Beneath serving as a patch panel for TEC power and control cables, the bulkhead contains services for the pixel detector. These pixel services are not part of the TEC geometry description and are described elsewhere.

The alignment ring also is contained in the TEC geometry description. Although not a tracker part, but rather a device from the CMS muon link system, the elements mounted on it (support structure, tilt meters, laser sources, shielding, ...) were simulated in the context of this document

Physically the carbon fibre compound rails are part of the TEC structure and have been simulated in the work described here. Due to geometric approximations of the TIB, TOB and TEC enclosing volumes the rails are contained in the volume of the Tracker Outer Barrel.

4 Validation of TEC geometry

Figure 6 shows a photograph of one TEC with all petals and services connected in a vertical position before transport to CERN next to a view of the simulated TEC as shown by the IGUANA [10] program.

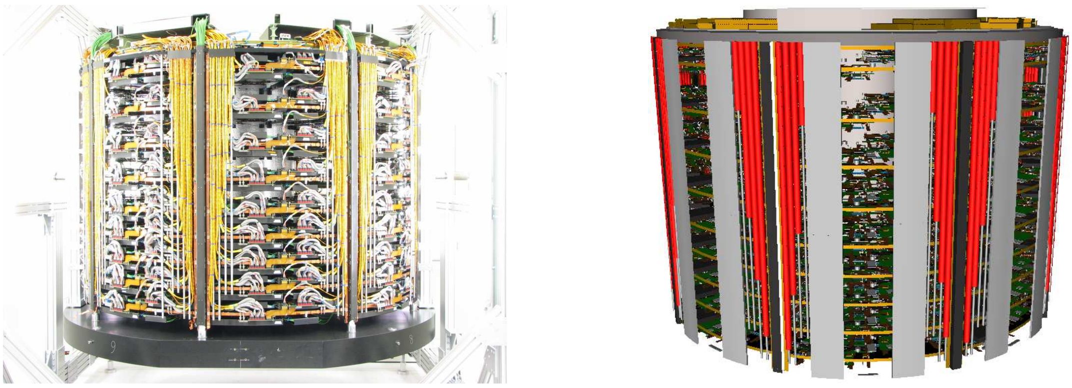

Figure 6: A photograph of one fully integrated TEC (left) next to its software representation (right) as visualized with the IGUANA program.

The structure built from disks and service channels can well be identified. Above and below the disks, petals are mounted with the silicon on the modules and the electronic components visible. The cooling pipes and the multi-service cables running along them are modelled with high accuracy, while the two large vertical grey box-shaped structures contain the bent cables forking from the cooling pipes and connecting to the petals, approximated by a smeared mixture since the slack and shape of the cables varies from disk to disk.

The validation of the software representation of the TEC geometry has two main objectives:

- Ensure that all elements of the description can be used in the GEANT4 simulation without software failures.
- Check that the description represents the physical TECs as closely as possible.

A tool named *DOMCount* was used to ensure XML correctness and a second tool named *ddreport* checked that the document followed the DDL specification. Another tool contained inside the GEANT4 suite allowed to verify that neither mother volumes overlapped with their daughter volumes nor daughter volumes overlapped with each other. This check was necessary because overlapping volumes lead to unpredictable GEANT4 behaviour, including endless loops.

The second goal was achieved by visual inspection with the IGUANA program, comparison of the material budget in terms of radiation length with earlier versions of the geometry and interpretation of the observed differences, verification of the simulated module positions with those from engineering drawings, and comparing the weights of simulated volumes with their real counterparts. Naturally the position of the active areas were of special interest in this endeavour.

4.1 Active materials

The geometry description is not only used to simulate the energy loss, multiple scattering and other possible interactions of particles traversing the passive material during the simulation. In both simulation and reconstruction, the active area of the silicon sensors plays an important role. While during simulation the strip position, orientation and length determines where a charge is sampled by the read-out electronics and subsequently converted by the reconstruction into a signal that is used for track fitting and thus determines the predicted CMS track resolution and physics performance, it has to coincide with the actual real tracker such that on physics data the same performance is obtained. The sensor thickness determines the amount of charge that is deposited and thus is important for dE/dx measurements as well as, together with the magnetic field, for Lorentz angle drift prediction. For modules in TEC rings 5, 6 and 7, two daisy-chained silicon sensors were mounted on one module frame and connected to the same readout-electronics which deserved attention during modelling.

For all reasons above, special care was given to an accurate description of the sensor layout. Reference [11] was used as a basis for the implementation of the silicon sensor description: Trapezoidal shape and size of passive and active area, radial[2)] topology of the strips, number of strips per sensor, sensor thickness. All the values were validated by reading the simulated geometry description in a CMSSW program, printing out all parameters, additionally simulating hits along different strips, and comparing by hand the obtained results to the sensor description and expected values.

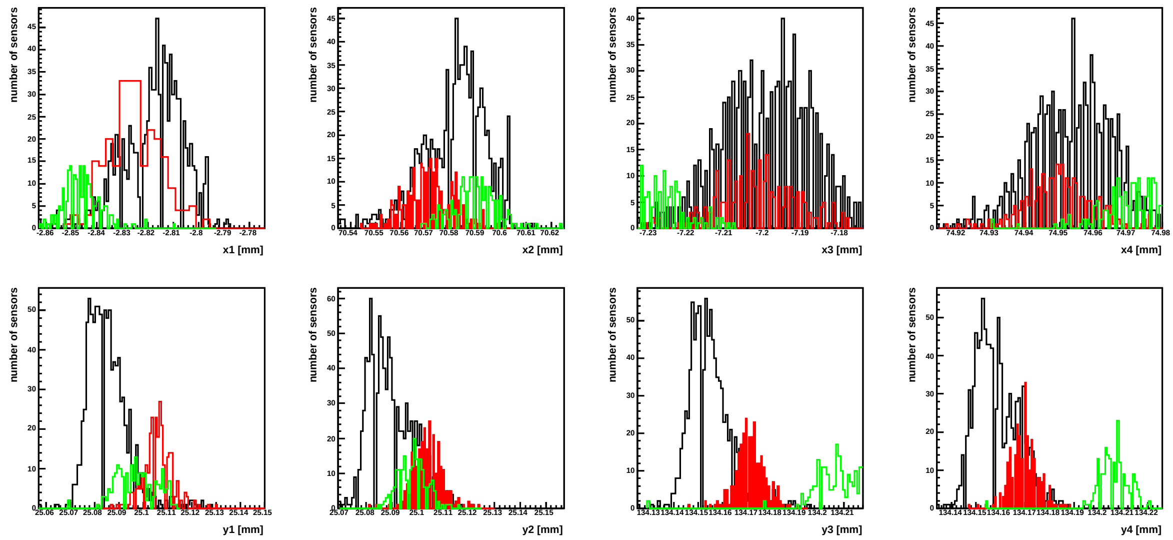

Figure 7: Coordinates (x_i, y_i) for four fiducial points on the ring 7 modules first sensor in the module frame for two assembly centers and two different sensor layouts: HPK sensors in Lyon (black), HPK sensors in UCSB (red) and ST sensors in Lyon (green).

The positioning of the sensors on the modules was obtained from engineering drawings and validated by measurements from the gantry robots with which the sensors were glued on the module frames. By doing this, small differences between different gantry centers could be spotted and some engineering drawings were updated accordingly. Figure 7 shows the coordinates (x_i, y_i) for four fiducial points on the ring 7 modules first sensor in

2) Although the sensor active area is of trapezoidal shape, the strips share a radial topology, i.e. have a constant angular distance and would intersect, if elongated, intersect in one single point.

the module frame for two assembly centers and two different sensor layouts: HPK sensors in Lyon (black), HPK sensors in UCSB (red) and ST sensors in Lyon (green). Within differences of the order of tenths of microns in the absolute positioning, the positions agree overall very well and correspond to the engineering drawing. All corrections which were deduced from the gantry measurements were implemented in the geometry description discussed here.

As next steps the position of the modules on petals was verified by comparing the positions of the precision mountings on a petal as specified in engineering drawings with survey information. The same procedure was repeated for petals on the disks and disks in the TEC. After all these validation steps were passed, the last step was comparing the absolute value of positions and orientations of the modules from the output of a dedicated CMSSW program with values deduced offline from the engineering drawings. Figure 8 shows the distance $r = \sqrt{(\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2}$ between engineering drawings and simulated geometry for all TEC modules. Due to unavoidable approximations, small differences remain. Overall the position of all modules in the simulation is within $15\mu\mathrm{m}$ of their nominal positions, which is much smaller than the misalignment of the modules due to mounting precision and thus sufficient for this geometry description.

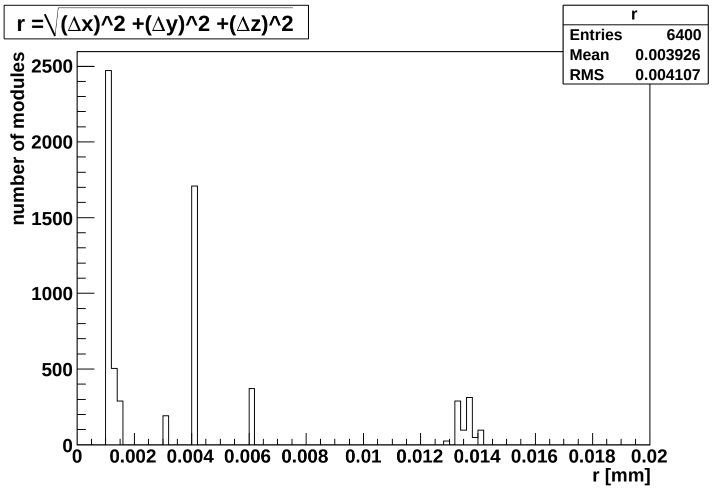

Figure 8: Distance in three-dimensional space between the module position as extracted from engineering drawings and the position as in the simulated geometry.

4.2 Passive materials

Due to the many approximations which were involved in the geometry description, the weights of the simulated volumes was compared with their real weight. This was done for individual parts as well as for simple and more complex assemblies and provided a powerful validation method. This required to weigh a large number of tracker end-cap objects.

4.2.1 Weighing of objects

Weighing of the constituents of the tracker end-caps was not done right from the beginning, but rather started beginning of 2005. Most materials and objects were still accessible at that time, with a few exceptions. For those exceptions weights were estimated from the known material density and the object volume which was computed from the engineering drawings. Some weighted samples like TEC disks were unique and, at the time of weighing, missing a few aluminium pieces. Therefore all accessible disk constituents (inserts, alignment pieces, laser beam-splitters, fixation brackets etc.) were weighed individually to be able to reconstruct the full weight. Other samples like petal inserts were available in abundance. In those cases several pieces were weighed together to extract a more reliable mean value. Figure 9 illustrates the weighing of ICB washers on the left hand side and weighing one full TEC on the right hand side.

For all measurements, a photograph of the object was taken and recorded with the weight and material composition in a table. The full range of measurements spans laser alignment, module, petal, disk, TEC and installation objects. The number of pieces weighed is given in Table 1 for each category. Comparing item by item missing objects in the simulation description were identified and added accordingly.

Figure 9: Weighing of washers for ICB mounting (left) and weighing the full TEC (right).

Category	Number of parts weighed
Module	36
Petal	111
Disk	40
Laser alignment	20
TEC	63
Installation	16
Sum	286

Table 1: Number of weighted parts according to their category.

After recording the weights, the multiplicity of all objects according to the engineering drawings was added to the table. This allowed a unique possibility for cross-checking the full description in simulation and reality simply by comparing the weights of combined objects which is described in the next section.

4.2.2 Weight Comparisons

Although in many cases the density of the simulated material has been extracted from the above weight measurements, a comparison between these and the simulated weight is an important cross-check. Some of these cross-checks are shown in the TWiki documentation for the TEC geometry [12]. The TWiki also contains a description of all used material mixtures. Here we describe some independent weight measurements.

Module weights The first validation was done by comparing the real module weights with those obtained from the simulated geometry. Since all modules were constructed by the same algorithm, some simplifications and approximations of the module structure were necessary, leading to unavoidable differences in the weights. The results of this validation step are shown in 2. An agreement within better than 6% is observed.

Petal measurement The petals are the most complex building blocks of the TEC, consisting of 525 up to 754 individual components for a back petal on disk 9 and a front petal on disks 1–3, respectively. The overall weight contribution of all petals to the TEC is 51%.

Volume Name	measured weight in g	simulated weight in g	difference in %
TECModule0	47.027	49.0	+4.2
TECModule1	53.545	56.2	+5.0
TECModule2	24.757	26.2	+5.8
TECModule3	24.628	25.9	+5.2
TECModule4	90.394	85.5	-5.4
TECModule5	45.604	44.1	-3.3
TECModule6	41.663	41.4	-0.6

Table 2: Comparison between measured and simulated weight for TEC modules.

As a further cross-check, an almost fully assembled long back-petal (see Fig. 10) has been weighed. The measured petal was missing some analog opto-hybrids, the digital opto-hybrid module, two small carbon-fiber protectors and two grounding cables. It consisted of 644 individual parts, and the measured weight of the petal was $2360\,\mathrm{g}$.

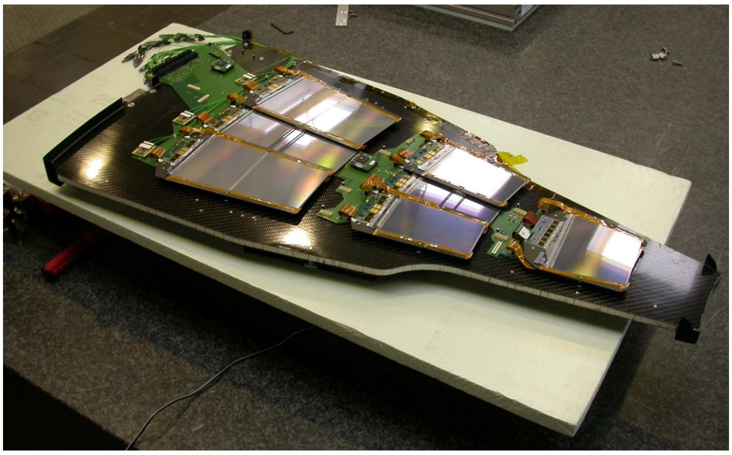

Figure 10: An almost fully assembled petal on a scale. The scale is hidden under the white shelf which serves as a support.

This measurement allows two systematic cross-checks. The first check is to estimate the systematic uncertainty in the geometry description from measurements only. Since all parts of the petal were individually measured, the weight of the petal can be predicted by the sum of the weights of all constituting parts. This weight is only correct if the counting of all components has been done correctly and the individual measurements have sufficient precision. This predicted weight was obtained to be $2330\,\mathrm{g}$, a difference of $-30\,\mathrm{g}$ or -1.3%. The difference can be explained by varying amounts of thermal grease, glue, solder, potting, number of plastic clamps used for the fibers, electrically isolating washers added irregularly in few places and differing from petal to petal etc.

The second cross-check is to compare the weight of the measured petal with the weight as obtained from the simulated geometry description. The simulated weight of a fully assembled long back petal (excluding the cooling fluid which was not present in the measured petal) is $2386\,\mathrm{g}$. A comparison to the petal weight measurement (adding the missing components mentioned above) of $2444\,\mathrm{g}$ reveals a small difference of $-58\,\mathrm{g}$ or $-2.4\,\%$.

TECs weight The finally assembled TECs were weighed just before they were installed in the CMS tracker in 2007 (Fig. 9b). Measured values of $734.4\,\mathrm{kg}$ and $730.1\,\mathrm{kg}$ were obtained for TEC+ and TEC-, respectively. This weight included some items like installation parts which were unmounted after the final installation of the TEC in the tracker support tube. This removed material amounted to 30.03 kg. The corrected TEC weights of $m_+ = 704.3\,\mathrm{kg}$ for TEC+ and $m_- = 700.2\,\mathrm{kg}$ for TEC- need to be compared with a weight of $m_{MC} = 691.7\,\mathrm{kg}$ as obtained from the simulated description, a mere deviation of 10 kg or 1.5% from the average TEC weight.

The small deviation of the number suggests a high accuracy of the TEC material description. From the several independent measurements described above we estimate that the systematic uncertainty on the simulated TEC weight is about 3%.

5 TEC material budget

The material budget normalized to one radiation length is shown on the left in Figure 11 as a function of η for all TEC parts (including the alignment ring). For reference, the same figure shows the normalized material budget for the full CMS tracker on the right. The amount is specified for different categories, with support elements contributing most overall for the TEC. At $\approx \eta = 2$, the largest contribution is from the cables, due to the patch panel on the bulkhead which contains many connectors as well as in- and outgoing cables. One should note that the material budget of the TECs is less than one radiation length over the full range of η.

Figure 12 shows an r-z-overlay of the TEC material budget, the remaining Tracker material budget and the TEC engineering drawing. The structure of the two TECs with the nine disks and the front- and back-petals is well visible, as well as the bulkhead region with the TEC patch panels.

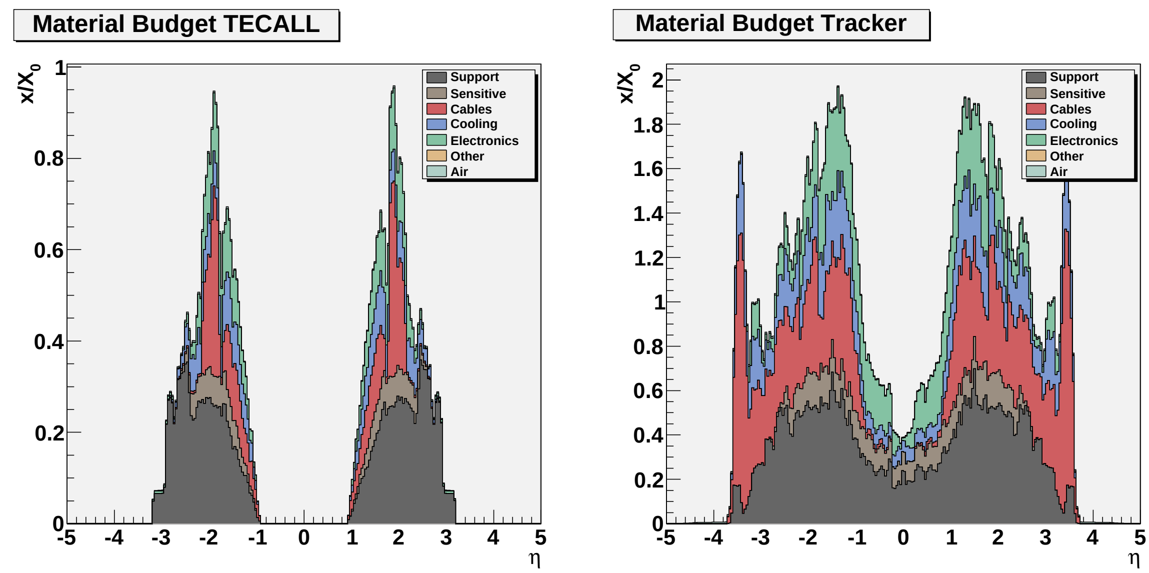

Figure 11: Material budget normalized to one radiation length as function of η for the TECs (left) and for the full tracker (right).

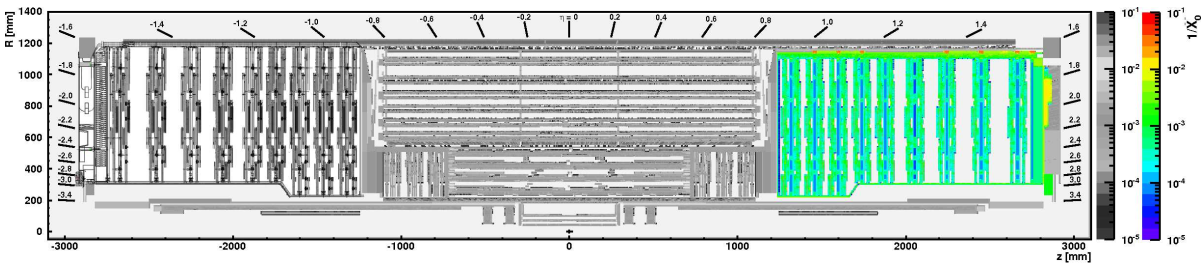

Figure 12: r-z-overlay of the TEC material budget (right, TEC+, colored), the TEC engineering drawing (left, TEC-, black) and the remaining material budget (grayscale).

6 Summary

The geometry and material budget description of the two CMS tracker end-caps (TECs) has been successfully implemented in the CMSSW software framework. In order to achieve this, the multiplicity, weight and material constitution of more than 280 individual parts has been recorded. Combined with information from engineering drawings, photographs and various other sources, an accurate description of the TECs was achieved. Due to software constraints, shape and position approximations of several volumes had to be made, while preserving the actual material. Several comparisons between the measured and predicted weight of the components were used to assess self-consistency of the description. Software-based validation ensured correctness of the description in CMSSW. The material budget of the TECs amounts to a maximum of 0.95 radiation lengths at $\eta \approx 1.8$ but is much less otherwise. The overall simulated weight of one TEC is 692 kg which compares well to an average measured weight of 702 kg.

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