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Alignment with infrared laser beams and silicon microstrip detectors

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ABSTRACT: In tracking detectors the precise alignment of the various sensor layers is important to allow efficient pattern recognition and precise track measurement. The alignment system for the CMS silicon microstrip tracker using infrared laser beams is presented. The laser beams traverse several layers of silicon sensors. The fraction of light which is absorbed in the silicon induces a signal which is used to monitor the alignment of the detector. This system will be able to monitor displacements of the mechanical structure of the detector with an accuracy better than 100 μm .

1. Introduction

The Compact Muon Solenoid (CMS) is one of the two general purpose detectors that will be installed at the future Large Hadron Collider (LHC). The inner tracker of the CMS detector consists of two parts: two layers of pixel sensors surrounded by a large silicon microstrip detector. In addition to tracking the pixel layers provide an excellent vertex measurement, while the microstrip sensors are also used to measure the momentum of charged particles. A detailed description of the CMS tracker can be found in [1, 2, 3].

For the proper operation of the silicon microstrip tracker it is essential that the several sensor layers can be aligned precisely with respect to each other. This is necessary for a robust track reconstruction and to get a good momentum resolution.

In the CMS experiment the higher level triggers, which are software implemented, make use of tracking information, making it necessary to reconstruct the tracks online at a rate up to 10 kHz. Powerful pattern recognition algorithms have been developed for this purpose. An alignment of the individual sensors to the level of a few hundred micron is needed for these algorithms to work reliably. The laser alignment system presented here has been designed for this purpose. Its goal is to measure the deformations of the mechanical support structure of the tracker with a precision better than 100 μm .

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For a precise momentum measurement an alignment of the order of the intrinsic sensor resolution is needed which is at the level of 10 μm . The laser system cannot provide this level of accuracy for all the tracker sensors. Since a very precise measurement of the momenta is not crucial for the online operation of the detector, this task will be performed offline using particle tracks.

2. Working Principle and Layout

The laser alignment system foreseen for the CMS tracker was inspired by a similar system in the AMS experiment, which has already been successfully tested [4]. It is based on the fact that silicon is partially transparent to infrared light. When aiming an infrared laser beam onto a silicon strip sensor, the absorbed fraction of the light will induce a signal in the strips as shown in figure 1. The transmitted fraction can travel further to another sensor where also a signal is induced. In this way several layers of silicon sensors can be traversed. Movements of the sensors with respect to each other can then be assessed from the positions of the measured beam profiles. In places where support structures or services obstruct a straight line, beam splitters can be used to route the light on a more complex path. This comes at the price of introducing inacccuracies due to imperfect beam splitter positioning.

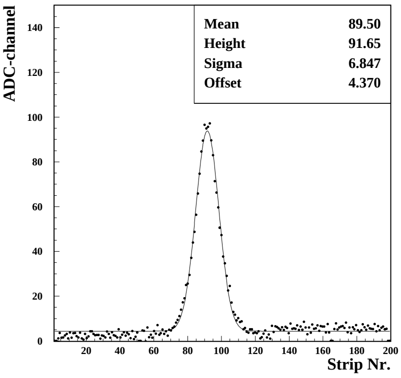

Figure 1: Signals induced in a silicon microstrip sensor by an infrared laser beam.

A key feature of this alignment system is that it uses the same sensors that also measure the particle tracks. In this way no new radiation hard sensors and readout electronics have to be developed and the amount of additional scattering material is minimized. Furthermore it becomes straightforward to relate the deformations that are measured by the laser system to corrections applied to the measured particle hit positions.

Figure 2 shows the layout of the laser alignment system for the CMS microstrip tracker [5]. It consists of four sets of beams denoted as Rays 1-4. Each set has several beams at different azimuthal positions. The laser sources can be laser diodes (1060-1080 nm) or Nd-YAG lasers (1064 nm) and are placed outside the CMS detector. The light is routed with fibers into the tracker volume, where collimators and beam splitters (indicated by the arrows) generate pairs of back-to-back oriented beams. Rays 2 and 3 consist of 8 beams each and are used for the alignment of the endcap disks with respect to each other. Ray 4 also uses 8 laser beams and aligns the endcaps with respect to the inner and outer barrel (TIB and TOB). Here beam splitters are used to get the light onto the TIB and TOB sensors. Finally ray 1 consisting of 6 laser beams is foreseen for the relative alignment of the entire tracker with respect to the CMS muon system. The collimators and beam splitters are placed so that the beams have to pass at most four layers of silicon sensors.

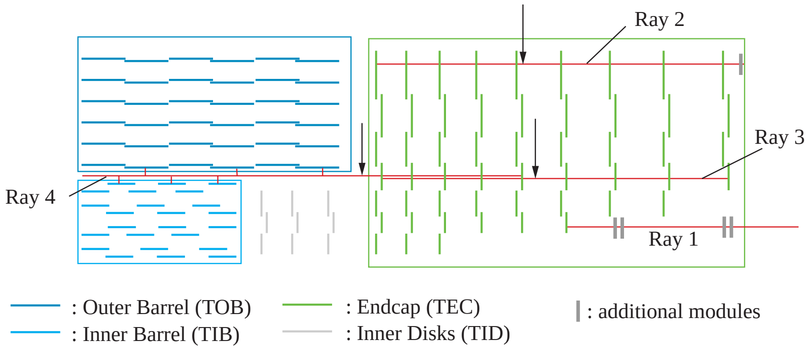

Figure 2: Layout of the laser alignment system for the CMS microstrip tracker.

3. System Performance

When traversing the silicon sensors with an infrared laser beam several effects take place which influence the alignment measurements. Reflection and absorption limit the intensity which is transmitted through one layer to approximately 20%. This will reduce the signal on the 5th layer to 0.16% of the initial intensity. As a consequence the signal to noise ratio (S/N) decreases by the same amount. Part of the signal loss can be recovered by averaging over a few hundred pulses which increases the effective S/N ratio. In this way it is possible to pass through 4 layers of silicon and still reach an effective S/N ratio of 10 on the 5th layer. It can also be envisaged to cover the silicon with an antireflective coating to minimize reflection losses, but this would mean a significant increase of the sensor costs.

Another disturbing effect is interference due to multiple reflections at the silicon-air interfaces. Depending on the thickness of the silicon sensor the interference can be constructive or destructive, changing the amounts of light that are transmitted, absorbed and reflected. If the thickness of a silicon sensor varies, the absorbed light intensity can become strongly modulated. This will lead to a distortion of the measured laser profiles and to a degradation of the accuracy. Using lasers with a small coherence length could minimize this interference. An antireflective coating would also be beneficial in this situation since it would eliminate the multiple reflections.

The accuracy Δm with which the intersection points of the laser beams with the tracker structure can be measured has several contributions. The precision Δm_{fit} with which the center of a perfect profile can be found is a function of the S/N ratio, the sensor pitch p and the laser beam width σ_L and can be approximated by $\Delta m_{fit} = \sqrt{\frac{8}{3\pi}(S/N)^{-1}}\sqrt{p \cdot \sigma_L}$. For our alignment system this gives a contribution of $\Delta m_{fit} \approx 20\ \mu\mathrm{m}$. The distortion of the profiles due to the interference leads to another contribution Δm_{dis} which scales with the laser beam width σ_L. We have measured this contribution to be $\approx 30\ \mu\mathrm{m}$. Since the surfaces of a silicon sensor are not perfectly parallel, the silicon will act as a prism and introduce kinks into the laser beams. Measuring the sensor thickness from the interference patterns yields the angle between the silicon surfaces and thus the kink angle in the laser beam. It was found that in the worst case this angle can become as large as 0.3 mrad, which can be converted to an additional uncertainty $\Delta m_{ref} \approx 30\ \mu\mathrm{m}$ in the determination of the intersection points. This is a very conservative estimate and we expect this error to be smaller in a real system. Finally the precision Δm_{mec} with which the sensors are mounted onto the mechanical structure will also contribute to Δm. This uncertainty is estimated to be around 50 μm . Adding up all the contributions in quadrature we obtain $\Delta m \approx 70$ μm .

To measure the deformations in the mechanical structure of the tracker, we first have to define a set of parameters which describe these deformations. As a first study this has been done for the endcaps which are aligned with rays 2 and 3 in fig.2. Since for these rays a collective rotation of all beams is indistinguishable from a rotation of the whole endcap in the opposite sense, the parameters are chosen so that collective rotations and torsions can be separated from the individual disk rotations. The same was done for the translations in the x and y directions. For one endcap and one set of beams we obtain the following parameters: translation in x and y and rotation around z for each disk $(\Delta x_k, \Delta y_k, \Delta\phi_k)$, two angles for each beam describing changes in its azimuthal position and orientation $(\Delta\theta_{ai}, \Delta\theta_{bi})$, collective translations and rotation of the endcap with respect to the beams $(\Delta x_0, \Delta y_0, \Delta\phi_0)$, collective shearing and torsion of the endcap with respect to the beams $(\Delta x_t, \Delta y_t, \Delta\phi_t)$. For 9 disks and 8 beams we end up with 49 parameters describing the movements of one endcap and a set of 8 laser beams. When the intersection points of beams and disks have been measured, the parameters are fitted to this data set.

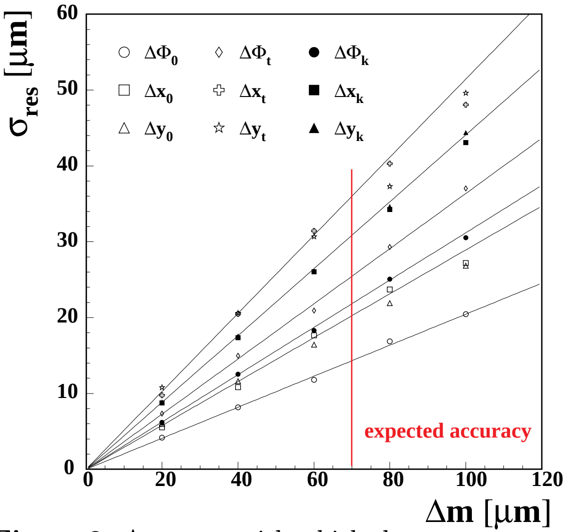

Figure 3: Accuracy with which the movements of one endcap can be measured as function of Δm.

The result of a simulation is shown in figure 3. The plot shows the accuracy with which the deformation parameters are reconstructed as a function of Δm. The symbols give the results of the simulation while the lines are an analytical calculation. For the expected measuring precision of 70 μm all parameters are reconstructed to better than 50 μm . Simulations in which the number of laser beams was changed show that even with only 4 laser beams the parameters are reconstructed to better than 100 μm for Δm=70 μm .

4. Conclusion

The alignment of the CMS microstrip tracker with infrared laser beams has been presented. A total of 52 laser beams will run through the tracker, each one shining on several modules. 32 of these beams perform the internal alignment of the endcaps, 8 beams align the tracker subdetectors with respect to each other. 12 additional beams perform the alignment of the tracker to the CMS muon system. The intersection points of the laser beams and the detectors can be measured with an accuracy of 70 μm . Deformations in the mechanical structure of the endcaps can be monitored with a precision better than 100 μm even if some laser beams are lost during operation. This is the level which is required for a robust track finding.

References

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