Alignment, status of the activity and impact on ATLAS and CMS first data

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Abstract
The ability to accurately align the tracking devices will be essential to fully exploit the ATLAS and CMS design performance. The general alignment strategy of the two detectors is presented, focusing, in particular, on commonalities and differences between the two procedures. A brief overview of the expected effects of misalignment on physics performance is also given.

1 Introduction
A precision alignment of the tracking devices is one of the most challenging calibration tasks that the ATLAS [1] and CMS [2] detectors will have to afford. Given the different design of the two experiments their requirements on the alignment procedures are quite different, as shown in Sec. 2.

The general alignment strategies are presented in Sec. 3. Both detectors developed optical systems for the measurement of the positions of their tracking devices with the primary goal of allowing an efficient and reliable pattern recognition and track reconstruction. However, the track based alignment procedure will play a key role in reaching the design performances of the tracking detectors both for ATLAS and CMS.

Finally, we present an overview of the expected impact of the misalignment on the reconstructed quantities and, as a consequence, on the physics performance of the two detectors, focusing, in particular, on the scenario that will probably characterize the first data taking.
2 Requirements on the alignment procedure

The tracking strategies of ATLAS and CMS are deeply different thus leading to completely different requirements on the calibration and alignment of their tracking devices.

ATLAS adopts a complex combination of two different magnetic field configurations for the measurement of particle trajectories: a 2 T solenoidal field in the Inner Detector (ID) [3] and a toroidal field in the Muon Spectrometer [4]. The ID is composed by three different detectors using different technologies. The highest granularity around the vertex region is provided by semi-conductor pixel and strip detectors, the latter employed in the Semiconductor Tracker (SCT). The pixels are capable of good two dimensional reconstruction with a resolution of 12 µm in the bending plane and 66 µm along z direction while strips have a better space resolution in the rφ plane (12 µm) than the z one (580 µm). A larger number of tracking points (about 30) is provided by the straw tube tracker also called Transition Radiation Tracker (TRT), giving a spatial resolution of 170 µm per straw. To fully exploit the ID design performance a knowledge of the alignment parameters at the level of the intrinsic detector resolution is required.

The ATLAS air-core toroids, providing a bending power in a range from 2 to 6 T · m, allow muon momentum measurements with large lever arm, degraded very little by multiple scattering. Both in the barrel and in the endcap regions the muon trajectory is sampled in three high precision stations equipped with Monitored Drift Tubes (MDT). Cathode Strip Chambers are used in the forward region, at 2 < |η| < 2.7. Each station measures the muon positions with a precision of about 50 µm. The φ coordinate in the non-bending plane is measured in the barrel region by Resistive Plate Chambers with a space resolution of about 1 cm. The required resolution on high p_T muon tracks force the alignment of the muon system to be kept within 30 µm.

The CMS detector is characterized by a compact design exploiting the large bending power provided by a 4 T solenoidal magnetic field. Charged tracks are bent in the transverse plane of the detector and their trajectories are measured by the Silicon Tracker detector [5]. This device employs 10 layers of silicon micro-strip detectors, which provide high granularity and precision with a resolution on the bending coordinate which ranges from 20 to 60 µm. In addition, 3 layers of silicon pixels are placed close to the interaction region. These detectors, with a spatial resolution in both coordinates of about 15 µm, heavily contribute to the improvement of the measurement of the impact parameter and vertex positions. The iron return
The yoke of the CMS magnet is instrumented with the muon spectrometer [6], composed by four stations of Drift Tube (DT) chambers in the barrel region and Cathode Strip Chambers (CSC) in the endcaps. Both in the barrel and in the endcaps Resistive Plate Chambers are used to give robustness and redundancy to the system.

The momentum resolution of the muon spectrometer is largely affected by the multiple scattering in the iron of the yoke. It is the Tracker which dominates the resolution up to very high $p_T$, of the order of $200−300$ GeV/c. Therefore the CMS spectrometer is subject to much less stringent requirements on the resolution of the chambers and on the knowledge of their alignment than the ATLAS one. For optimal performance over the entire momentum range up to 1 TeV/c, the chambers must be aligned with respect to each other and to the central tracking system within $100−500$ µm. On the other hand, the CMS design leads to very stringent requirements on the Tracker alignment: to fully exploit the intrinsic resolution of the silicon detectors the knowledge of the alignment parameters up to the level of the ideal track parameter resolution is needed.

While some sources of misalignment, as the construction and assembly tolerances, will not change during the whole experiment life others will require a continuous monitoring, for example the movements due the opening and closing of the detectors and the deformations induced by the magnetic field. The overall effect can result in the displacement of the muon chambers with respect to their nominal positions of up to a few centimeters and the reproducibility of those movements will be in general limited to some millimeters. More important for the central trackers are the effects of thermal instabilities which can cause dynamic misalignments at the sub-millimeter level.

3 General alignment strategy

Only a track based alignment strategy can cope with the requirements illustrated in Sec. 2. However, such a strategy cannot be used standalone since it relies on an efficient pattern recognition and track reconstruction. For this reason both ATLAS and CMS developed a procedure based on different steps. First of all the measurements and surveys performed during detector construction and accounting for the mechanical precision of the apparatus will be used as a starting point of the alignment parameters. The second step will exploit the measurement of the positions of the tracking devices deriving from the optical alignment systems and it will play a central role
for the first tracking performances. Finally, the track-based alignment will be used to reach the design knowledge of the detector positions.

As far as the test of the alignment procedure is concerned, the two experiments are in a quite different situation. The combined test beam of the ATLAS detector has been an important benchmark for the full alignment strategy [7], as shown in the following. On the other hand, the CMS scheme will partially be validated during the solenoid test, where about 1/3 of the Muon Alignment system will be implemented instrumenting two sectors of barrel DTs and one complete endcap disk.

### 3.1 Optical alignment systems

ATLAS will adopt an optical system for the alignment of the muon spectrometer only, while particle tracks will have to be used for aligning the ID and for determining the relative position of the two tracking devices. The muon alignment system [8] is based on optoelectronic sensors that measure the relative positions and the deformations of the MDT chambers. In addition, temperature sensors monitor their global thermal expansions. In the barrel part, the optical sensors are placed directly on the chambers, whereas the alignment of the endcap part makes use of a set of intermediate optically and temperature controlled aluminium bars carrying optical sensors to measure their relative positions and to relate them to neighboring chambers.

Two types of sensors are used: a 3-point alignment device, the RASNIK [8] and a camera system SACAM. Both systems allow to measure precisely (to a few microns) the departure from a straight line of the transverse position of the optical elements and less precisely (to a few hundred microns) their relative position along the optical axis by using the magnification.

Two alignment modes (relative and absolute) are possible and were tested in the Combined Test Beam [7]. In the relative mode it is assumed that the MDT chamber positions are known at a given time (these positions are input to the so-called reference geometry); the optical sensor responses are used to infer the subsequent chamber movements with a precision better than 20 µm. In the absolute mode the position of the chambers is calculated using only the current measurements of the optical sensors; this mode requires an accurate calibration of all the alignment parts. The optical alignment system must measure the relative position of the inner, middle and outer muon stations with an accuracy such that the maximum alignment contribution to the sagitta measurement is less than 30 µm. The test beam data show that, in the relative mode, the precision is of the order of 20 µm. For the absolute mode, which was tested for the first time in 2004,
the mean value of the sagitta is known with a 350 μm uncertainty in the barrel and 150 μm in the endcap. The remaining shift from zero (the theoretical sagitta value for straight tracks) is expected to be reduced significantly once the final calibration of the optical alignment sensors is available.

The CMS optical alignment system is composed by three main parts: the Muon Alignment (MA) system, the Laser Alignment System (LAS) for the Tracker and a Link System which will connect the tracker and muon spectrometer. The MA is described in detail in [6]. It consists of 3 r – z alignment planes, one every 60 degrees in φ, linking together the the central tracker, the barrel and endcap muon detectors. The system uses two types of light sources, LED and laser beams, to determine the three dimensional position of the four chamber corners of all the 250 DT chambers and of almost the 23% of the CSC chambers (for the remaining CSCs the overlap between the chambers will be used). The MA is designed to monitor the detector geometry continuously, with or without collisions, covering the whole range from 0 to 4 T magnetic field. The design resolution of the MA in the standalone measurement of the geometry of the muon spectrometer is close to the final requirements being of about 200 μm for displacements in the bending plane. These numbers are confirmed by the test of half alignment plane performed in the ISR hall at CERN [9]. The LAS uses infrared laser beams to monitor the positions of the tracker subdetectors TIB, TOB and TEC (not including the pixel detector and the TID) with respect to each other. It cannot determine the position of individual modules but only of composite structures. It’s goal is to reach, in combination with survey measurements, a precision of about 100 μm on the position of the silicon sensors which is the baseline for an efficient pattern recognition. The CMS optical alignment system is designed to take data continuously completing a full cycle of measurements several times per hour.

3.2 Alignment with tracks

The alignment with the tracks is fundamental in ATLAS because is the only way, after the survey measurements during the commissioning, to align the ID itself and the ID with the Muon Spectrometer. The techniques for the alignment of the ID are based on χ² minimization or Kalman filter algorithms. The huge number of degree of freedom for the geometrical position of the detectors and their distortion leads to a step procedure for a global alignment. First of all the innermost layer of pixel detectors are aligned among themselves, then the SCT strips are aligned with respect to pixel and, finally the TRT tubes are aligned, after the calibration, with the semi-
conductor detectors. The results of the 2004 Test Beam data [10] have shown that the statistical error on the alignment parameters is well under control ($\approx 10 \, \mu m$), and the systematic error ($\approx 30 \, \mu m$) is the most important contribution to be kept under control, requiring more statistic to be evaluated. Problems could arise only if the starting point of the track based procedure (given by the surveys data) is considerably far from the the real situation: this problem could affect the pattern recognition efficiency. Also the results of the track based alignment of the Muon Spectrometer with respect to the ID [7] show that the required resolution of the alignment could be easily reached in few days of data taking.

The track based alignment of the CMS Tracker will be crucial not only because it has to reduce the uncertainties deriving from the LAS measurements of a factor 10 but also because it will be the only available strategy for the pixel detector. In fact, this device, which will only be installed after the 2007 LHC pilot run, cannot be aligned with the laser beams. At the moment three different track-based alignment algorithms are considered for the Tracker, each of them proposes a different approach to the major challenge of determining $O(100000)$ alignment parameters. The hits and impact point (HIP) algorithm [11, 12] is an iterative method which relies on a fit to data of an analytical expression of the residuals as a function of the alignment parameters. Another method is based on an iterative procedure which updates the alignment parameters after each track using a Kalman filter [13]. The MILLEPEDE algorithm [14, 15] is based on an overall least-squares fit to data including track and alignment parameters.

As far as the muon spectrometer is concerned the track-based alignment will complement the MA system since it will provide a precision similar to that of the optical device but with a totally independent strategy and therefore with totally independent systematic uncertainties. Considering that the construction and assembly tolerances will be already accounted for by the survey, optical and cosmic-ray measurements, the chambers can be viewed as rigid bodies. As a consequence the muon alignment involves a relatively small number of parameters but with the additional difficulties deriving from the fact that the various involved subdetectors are separated by a large amount of material and the tracks traveling from the Tracker to the spectrometer will cross a nonuniform magnetic field. Two alternative approaches are proposed [16]: one for the alignment of the muon system with respect to central Tracker and another for the standalone spectrometer alignment. The first one is based on the extrapolation to the muon system of an isolated muon track reconstructed using the Tracker only. The result of the extrapolation is then compared with the local reconstruction in each
muon station, decoupling the alignment of each muon chamber. The alternative approach can also be used if the Tracker misalignment will be too large for full track reconstruction, in this case the Blobel [14] method will be exploited.

The basic data sample for the track based alignment will be inclusive high $p_T$ single muons. This sample will be complemented by dimuon sample coming from the $Z$ decay which further has the advantage that the mass constraint can be exploited. The cut on the transverse momentum must balance the statistics available and systematics. Considering that already at the luminosity of $2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ approximately 20000 $Z \rightarrow \mu^+\mu^-$ and 100000 $W^\pm \rightarrow \mu^\pm \nu$ will pass the HLT selection per day a few days will be enough to reach the needed statistical uncertainties of 100 $\mu$m in the determination of the muon system alignment parameters while 1 or 2 weeks of data taking should be sufficient for the alignment of the entire Tracker. The major systematic uncertainties will be the knowledge of the material budget for what concerns the Tracker and, in addition, the knowledge of the magnetic field outside the Tracker volume for what concerns the muon system. An additional sample will come from muons from cosmic-rays. Already the CMS Cosmic Challenge is expected to provide much more precise informations on the achievable precision with the described procedure. It is also under study the possibility of triggering beam-halo events using the TOTEM [17] T1 telescope for the Tracker alignment.

4 Impact of alignment on physics

The main effort in the ATLAS collaboration is to evaluate, in the commissioning period, mainly through cosmics tracks, the alignment of the ID [18]. A realistic scenario of initial misalignment of this detector, can correspond to a knowledge of the sensor positions at the level of 100 $\mu$m from the survey data. This leads to a loss in the track reconstruction efficiency of about 20% for isolated tracks, and one order of magnitude in resolution. The tracking efficiency could be recovered relaxing the cuts on the “goodness of the track”. To reach the design knowledge of the alignment parameters starting from this scenario will require a statistics corresponding to several millions of reconstructed tracks.

Also in the CMS Collaboration the effect of the misalignment on the measurement of the track parameters has been studied considering two different stages of the detector operations: the “First Data Taking” and the “Long Term” scenarios [19]. The first one corresponds to the expected mis-
alignment conditions during the first period of running up to a collected luminosity of the $\mathcal{O}(100 \text{ pb}^{-1})$. The Tracker is assumed to be aligned using the LAS for the strips and a first track-based procedure for the pixels, achieving a resolution on the positions of about 100 $\mu$m and 10 $\mu$m respectively. The “Long Term” scenario corresponds to the level of knowledge of alignment parameters foreseen after a luminosity of the $\mathcal{O}(1 \text{ fb}^{-1})$, the basic hypothesis in this case is that the track-based alignment would reduce the placement uncertainties of a factor 10. The effects on the track reconstruction for the different scenarios of Tracker alignment are shown in Fig. 1 [21] for single muons of 100 GeV/c momentum. Also for CMS the misalignment of the tracking device leads to a loss of track reconstruction efficiency. The strategy adopted to recover the efficiency drop is to take into account the alignment position errors. The resolution on the transverse momentum, in the central region is degraded to almost the 5% in the “First Data” scenario. The effect of the misalignment of the muon chambers [20], which positions in the “First Data” conditions are supposed to be known at the mm level, is relevant only for very high $p_T$ tracks.

References


