A Self Seeded First Level Track Trigger for ATLAS

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ABSTRACT: For the planned high luminosity upgrade of the Large Hadron Collider, aiming to increase the instantaneous luminosity to $5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, the implementation of a first level track trigger has been proposed. This trigger could be installed in the year $\sim$2021 along with the complete renewal of the ATLAS inner detector. The fast readout of the hit information from the Inner Detector is considered as main challenge of such a track trigger. Different concepts for the implementation of a first level trigger are currently studied within the ATLAS collaboration. The so called "Self Seeded" track trigger concept exploits fast frontend filtering algorithms based on cluster size reconstruction and fast vector tracking to select hits associated to high momentum tracks. Simulation studies have been performed and results on efficiencies, purities and trigger rates are presented for different layouts.

KEYWORDS: Particle tracking detectors; Trigger algorithms; Trigger concepts and systems.

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1. Introduction

It is foreseen to increase the luminosity of the Large Hadron Collider (LHC) in the year \( \sim 2021 \) to \( 5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1} \), to exploit fully the discovery potential of the accelerator. To cope with the higher rates and irradiation dose it is also planned to renew the complete inner detector of ATLAS. First studies [1] have shown that without improvements of the trigger and the data acquisition system, trigger thresholds would have to be significantly raised to cope with the higher rates, thus compromising the analysis of many physics search channels. Therefore, the implementation of a new first level track trigger has been proposed, which would improve the selectivity for electrons, muons and taus by combining information from different subdetectors already at the first trigger level. The feasibility of implementing a fast track processor using hit pattern lookup techniques was already discussed at the previous workshop [2].

Because of the high particle rates at an upgraded LHC machine it is impossible to read out the complete hit information from all tracks for every bunch crossing. This problem can be tackled by using hits only from selected trigger layers and in addition by applying hit filtering techniques at the frontend. In the so called L0/L1 readout scheme, requiring the implementation of the new trigger level L0, external L0 trigger information from the calorimeter and muon system are used to define regions of interest, which are then read out and processed by a fast track reconstruction [1].

In the Self Seeded Track Trigger scheme hits are locally processed at the frontend to identify high transverse momentum \( (p_T) \) tracks. Only hits consistent with coming from high \( p_T \) tracks are read out and further processed in the track trigger.

Both concepts are complementary. The L0/L1 scheme with regional readout allows the reconstruction of tracks down to very low momenta and the use of track isolation criteria. It provides
additional track information in regions which are externally selected by calorimeter and muon triggers. In contrast, the Self Seeded Track Trigger finds all high momentum tracks in the event and provides independent information at the first trigger level, thus increasing redundancy. For example, by combining high $p_T$ tracks with an energy veto in the calorimeter it would be possible to set up an alternative trigger for minimum ionising particles (muons, new exotic particles, etc.) as depicted in figure 1 left. Both concepts can also be combined by installing the Self Seeded Track Trigger at a new trigger level L0.

In the following first simulation results of the Self Seeded Track Trigger concept are presented.

2. Simulation

The simulation is based on the Utopia design for the upgraded ATLAS tracker. Simulation studies are performed for the barrel region only, which consists of four axial layers of pixel detectors, three layers of double-stacked strip sensors of length 2.5 cm and two layers of double-stacked strip sensors of length 10 cm. A sketch of the overall geometry is shown in figure 1 right.

A track trigger based on layers of strip sensors with 80 µm pitch is studied using different layer geometries. Details of the performed simulation study can be found elsewhere [3]. Signal events are simulated using single high $p_T$ muons and antimuons. For comparison also single electrons and pions are used. Background is simulated using minimum bias events as generated by PYTHIA [4] with pileup scenarios of up to 400 events per collision. In order to test the influence of pileup on the signal efficiency, single high $p_T$ muons are implanted in minimum bias events. Events are simulated using the ATLAS ATHENA framework [5] based on the GEANT4 simulation package [6].

Three different sets of strip layer combinations are studied as sketched in figure 1 right. Note that the different layer combinations cover different pseudorapidity regions, resulting in different

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acceptances and trigger rates.

3. Frontend Hit Filtering

The used frontend filtering algorithms, the cluster size method and the offset method [3] are shortly summarised here. The implementation of these algorithms in the frontend ASIC was presented at this workshop [7].

3.1 Cluster Size Method

The cluster size of adjacent silicon strips is reconstructed online on frontend chips. Due to the strong solenoidal magnetic field low $p_T$ tracks are strongly bent and hit the sensors under a larger inclination angle than high momentum tracks, leading to charge sharing over several adjacent strips. The resulting cluster sizes as function of transverse momentum are shown in figure 2 for muons. Note that the response of particles is different for particles and anti-particles for the used Utopia design, in which the strip sensors are tilted by 10 degrees. A cluster size cut of $N_{\text{cluster}}^{\text{strip}} \leq 2$, which will be used in the following, represents a good compromise between rejection of hits originating from low momentum tracks and keeping high efficiency for hits from high $p_T$ tracks.

3.2 Offset Method

Each layer is made of $10 \times 10$ cm$^2$ modules consisting of two stacked strip sensors with a gap of 7.35 mm. In the standard Utopia design both layers are inclined relative to each other to allow for stereo angle measurements to determine the hit $z$-coordinate. For track trigger studies this angle is set to zero. By matching the corresponding hits between the inner and outer sensor, the azimuthal distance of the hits is a measure of the transverse momentum under the assumption that the particle originates from the beamline. By defining a window of allowed offset values, local hit coincidences corresponding to high transverse momentum tracks with $p_T > p_T^{\text{offset}, \text{min}}$ are selected.
The offset method takes also the sensor tilt into account, which leads to an asymmetric window of accepted offsets.

3.3 Results

The fraction of rejected electron, pion and muon hits normalised to the total number of hits produced by the particle are shown in figure 3 left. High rejection values are aimed for to reduce the readout bandwidth. Clearly visible is the much lower effective $p_T$ threshold of the cluster size cut compared to the offset method using $p_{T, \text{min}}^{\text{offset}} = 10$ GeV. The results are calculated from all hits originating from the particle, including secondary (and tertiary) interactions, which are most prominent for electrons but also important for pions and to a lesser extend for muons.

The fraction of rejected hits in minimum bias events is shown in figure 3 right as function of $p_{T, \text{min}}^{\text{offset}}$ for different pileup scenarios. The results are obtained using the offset method only and using cluster size cut and offset method combined. The combined method has a better rejection power as the confusion problem in the hit matching is reduced by applying the cluster size cut first. The combined method is notably more robust at high pileup rates.

The fraction of hits passing the filtering algorithm for $p_{T, \text{min}}^{\text{offset}} = 10$ GeV are given in table 1 for each strip layer with and without the cluster size cut. Rejection factors of about 25 (12-20) are possible if the cluster size cut is included (excluded). In the inner layers the fraction of accepted hits is further reduced if only hits in the projected pseudorapidity ranges are considered.

4. Global Track Reconstruction

Hits from two or three strip layers, according to the geometry under study, are combined after passing the local filtering algorithms and then helix fitted. In a hardware trigger, this step would be
Table 1. Fraction of accepted hits using the cluster size cut and offset method with $p_{T\text{, min}} = 10$ GeV. The fractions of hits passing the offset method without cluster size cut are given in brackets. The calculation is done for all hits and only for those in the projected geometry of the layers $#2 (|\eta| < 1.4)$ and $#4 (|\eta| < 1.0)$, see figure B normalised to the total number of hits per layer. SS denotes short strip and LS long strip layers.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Fraction of accepted hits in percent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Full barrel</td>
</tr>
<tr>
<td>Layer 0 (SS)</td>
<td>4.0 (6.4)</td>
</tr>
<tr>
<td>Layer 1 (SS)</td>
<td>3.4 (5.5)</td>
</tr>
<tr>
<td>Layer 2 (SS)</td>
<td>3.2 (5.1)</td>
</tr>
<tr>
<td>Layer 3 (LS)</td>
<td>4.5 (8.0)</td>
</tr>
<tr>
<td>Layer 4 (LS)</td>
<td>4.0 (6.5)</td>
</tr>
</tbody>
</table>

Figure 4. Top: Trigger efficiency of $p_T = 40$ GeV muons versus normalised trigger rate for different trigger layer sets and pileup scenarios including frontend filtering (cluster size + offset method) in all used layers. The data points are shown for different $\chi^2$ cuts of the track fit. A lower cut value reduces the reconstruction efficiency. Bottom: Efficiency versus purity. Otherwise same as upper plot.

realised by fast pattern matching in associative memories, similar to what is planned for the Fast Tracker project [8] at ATLAS.
The performance of the track reconstruction and the fake track rejection depends on the $\chi^2$ cut applied to the fit. For $p_T = 40$ GeV muons the track finding efficiency versus number of reconstructed tracks per bunch crossing and versus purity is shown in figure 4 for different $\chi^2$ cuts, for different layer sets, and for different pileup scenarios. It can be seen that the layer set #34 has very low purities and leads to high trigger rates. This can be explained by the fact that the two outer long strip layers do not provide sufficient redundant hit information to reject combinatorial background. Requiring purities of at least 50%, track finding efficiencies of about 80% (75%) for 100 (200) pileup events can be reached with the setups #012 and #234.

The track finding efficiency is significantly higher if no cluster size cut is applied as shown in figure 5. However, in this case also the trigger rate increases due to the higher fake rate. Efficiencies and purities of about 100% are reached in the “no pileup” scenario, see box in figure 5. In this case the strip occupancy is very low, thus resulting in a very low fake rate. The no pileup scenario corresponds to a high pileup scenario with much higher detector granularity, which could by realised in alternative designs either by using millimeter long strixels or pixels instead of (long) strips.

The same study is repeated using higher $p_T$ thresholds in the offset method. For cluster size cut and offset method combined with $p_{T,\text{min}}^{\text{offset}} = 15$ GeV, track rates of about 0.01 – 0.02 tracks per collision for 200 pileup events are found for the layers sets #012 and #234 at a track finding efficiency of about 75%. This corresponds to a trigger rate of $0.5 - 1$ MHz for $p_T > 15$ GeV particles at a proton-proton collision frequency of 40 MHz. Again slightly higher efficiencies at the cost of higher fake rates are obtained by not applying the cluster size cut.

The origin of the track reconstruction inefficiencies is studied in detail for the discussed designs with three layers. The main loss comes from the (conservative) single hit efficiency of 98% as used in the simulation and from the requirement that hits in all three double layers are required in the track matching, leading to an inefficiency of 12% in the track finding. Also the cluster size cut with an inefficiency of 1% per layer (total 6%) has significant impact. Other inefficiencies induced by the offset method or by the track fit ($\chi^2$-cut) contribute only with about 1% to the total track finding inefficiency.

**Figure 5.** Trigger efficiency of $p_T = 40$ GeV muons versus purity using the offset method only. For description see figure 4. In the right inset results are shown for a scenario without pileup for comparison.
5. Summary

The feasibility of a Self Seeded First Level Track Trigger for reconstructing all high $p_T$ tracks in an event was studied using a detailed ATLAS detector simulation. Such a trigger would add complementary trigger information to the ATLAS trigger system.

Designs based on stacked strip silicon sensors are simulated. The simulation includes frontend filtering algorithms to reduce the readout bandwidth using the cluster size cut method and the offset method, which both identify locally hits originating from high momentum particles. These filtering techniques allow to reduce the bandwidth by factors of about 12-25. The offset method is found to be highly efficient whereas the cluster size method is found to have inefficiencies on a percent level per sensor. The resulting hits are input to a global track fit. By matching hits from three strip layers, a good rejection of fake tracks is achieved. Track trigger rates of the order of 1 MHz for single high transverse momentum tracks $p_T > 10 – 15$ GeV are reached at reasonable track finding efficiencies. Such a trigger rate would fit in to the proposed L0/L1 trigger scheme but could also be further reduced using higher thresholds.

The track finding efficiencies are very sensitive to the single hit efficiencies as hits are required in all used layers in the studied designs. Higher track finding efficiencies could be reached if one or more of the following design actions are taken: A) no cluster size cut at the cost of higher readout bandwidth and higher trigger rates, or B) use of more than three strip layers to increase the redundancy and fallback safety in case of missing hits in the track trigger system. The latter is also beneficial for improving the purity and thus reducing the fake rate. More redundancy and higher efficiency compared to the studied three-layer designs can be achieved simultaneously by implementing a 4/5 layer coincidence. Alternatively the use of very short strips or strixels should be considered, which would lead to lower detector occupancies and therefore reduce the fake rate.

References