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Fast track segment finding in the Monitored Drift Tubes of the ATLAS Muon Spectrometer using a Legendre transform algorithm

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Abstract. The upgrade of the ATLAS first-level muon trigger for High-Luminosity LHC foresees incorporating the precise tracking of the Monitored Drift Tubes (MDT) in the current system based on Resistive Plate Chambers and Thin Gap Chambers. This update aims to improve the accuracy in the transverse momentum measurement and control the single muon trigger rate by suppressing low quality fake triggers. The core of the MDT trigger algorithm is the segment identification and reconstruction which is performed per MDT chamber. The reconstructed segment positions and directions are then combined to extract the muon candidate's transverse momentum. A fast pattern recognition segment finding algorithm, called the Legendre transform, is proposed to be used for the MDT trigger, implemented in a FPGA housed on a ATCA blade.

1 Introduction

Many of the physics goals of ATLAS [1] in the High Luminosity LHC (HL-LHC) era, including precision studies of the Higgs boson, require an unprescaled single muon trigger with a 20 GeV threshold. The selectivity of the current ATLAS first-level muon trigger is limited by the moderate spatial resolution of the muon trigger chambers. By incorporating the precise tracking of the MDT, the muon transverse momentum can be measured with an accuracy close to that of the offline reconstruction at the trigger level, sharpening the trigger turn-on curves and reducing the single muon trigger rate. A novel algorithm is proposed, based on the Legendre transform [6] which identifies and reconstructs segments from MDT hits in an FPGA within the tight latency constraints of the ATLAS first-level muon trigger. The algorithm represents MDT drift circles as curves in the Legendre space and returns one or more segment lines tangent to the maximum possible number of drift circles. This Legendre transform algorithm does not require the resource and time consuming hit position calculation and track fitting procedures and can be thus realised in a low-latency pure-FPGA implementation. The reconstructed MDT segments are then combined to calculate the muon's transverse momentum (p_{T}) with a parametric approach which accounts for varying magnetic field strength throughout the muon spectrometer.

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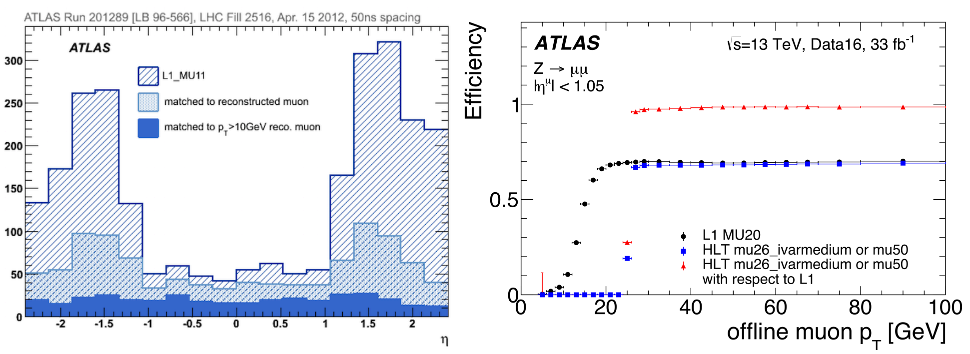
2 The ATLAS Muon Trigger system

The ATLAS muon spectrometer is divided in ϕ into 16 sectors. It is further partitioned between barrel and endcap subsystems, A and C sides (divided at $\eta = 0$), and three layers (inner, middle, and outer). It consists of four different gaseous detector technologies namely Cathode Strip Chambers (CSC), MDT, Resistive Plate Chambers (RPC) and Thin Gap Chambers (TGC). CSCs and MDTs, due to their excellent spatial resolution are used for precise muon track reconstruction while the RPC and TGC are fast detectors that provide trigger primitives. The first level muon trigger decision is at the moment performed using coincidences of RPC/TGC hits along the different detector layers [2]. The trigger algorithms are executed in the so-called Sector Logic (SL) boards that provide the muon trigger candidates as output.

2.1 Limitations of the current system

There are several limitations in the current system that necessitate the upgrade of the muon detectors as well as the muon trigger system in order to maintain and even improve the current performance at HL-LHC. One of the main limitations arises from the fact that the muon trigger rate in the endcap region ($|\eta| > 1.05$) is dominated by fake triggers. As can be seen in Fig. 1a most of the trigger candidates in this region are not matched to offline reconstructed muons. These are caused by slow charged particles not originating from the Interaction Point (IP) that their track footprint over the TGC detection layers produces a fake IP-pointing segment. In addition, the current trigger efficiency in the barrel region ($|\eta| < 1.05$) is limited to $\sim 70\%$ due to the geometrical acceptance of the RPC chambers coming from the detector structure. Moreover, the current trigger chambers RPC & TGC are characterised by a limited spatial resolution purely attributed to the detector technology. This results in a moderate p_{T} resolution which in return is translated in a rather shallow efficiency turn-on curve as can be seen in Fig. 1b.



(a) (b)

Figure 1: Limitations of the current muon trigger system in trigger rate and efficiency: (a) η distribution of muon trigger candidates [3], (b) Muon trigger efficiency as a function of p_{T} [4]

2.2 Upgrade for HL-LHC

A graphical representation of the upgraded first level muon trigger logic is presented in Fig. 2a. To tackle the issue of fake triggers in the endcap region New Small Wheels (NSW) will replace the current small wheels providing an additional high resolution trigger segment that can be used for suppressing the TGC SL fake candidates. In order to improve the barrel trigger acceptance an extra layer of RPCs will be installed in the inner layer [4]. In addition, the MDT precision information will be used in the first-level trigger improving the sharpness of the muon p_{T} threshold. The different elements of the ATLAS muon trigger system for HL-LHC are shown in Fig. 2b.

The MDT Trigger Processor (TP) will be receiving the MDT data from the front-ends and will combine them with the RPC/TGC-NSW trigger candidates that are produced by the Sector Logic (SL) boards. It will then provide a precise calculation of the candidate's p_{T}. The MDT trigger will help to alleviate the extremely large cross section for muons with $p_{\mathrm{T}} < 20\,\mathrm{GeV}$ mis-measured above threshold, improving the muon trigger purity. It will also provide an additional handle to reduce fake triggers generated by low-quality RPC/TGC trigger coincidences allowing to keep the trigger rate under control at HL-LHC conditions.

2.3 The ATLAS MDT trigger for HL-LHC

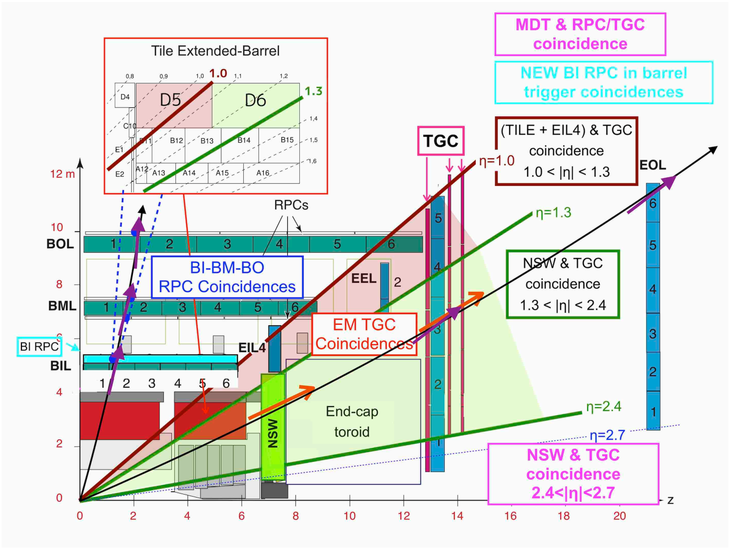
The basic functional blocks of the MDT TP design are depicted in Fig. 3. The MDT hits undergo a time-calibration procedure and are then matched to a region of interest (RoI) and to a reference time determined by RPC/TGC SL. The next main step is the identification and reconstruction of segments at the different MDT stations that are then combined to determine the muon p_{T}. Since the MDT chambers are superior to the RPC and TGC in terms of spatial resolution, a muon p_{T} resolution close to that of the ATLAS offline reconstruction algorithm can be achieved at the trigger level.

Depending on the number of segments can be reconstructed per muon candidate in the different MDT stations, two separate methods can be used for the p_{T} determination [4]. If three segments are found (applicable to 73% of the muons), with each in a different MDT station, their positions can be combined to measure the track curvature by calculating the sagitta out of the three points (3-station method). However, it may happen that a segment cannot be found in all three MDT layers (i.e. geometrical acceptance constraints). In these cases (applicable to 21% of the muons), two segments in different MDT stations can be combined to extract the p_{T} by measuring their deflection angle (2-station method). The MDT trigger algorithm should provide a measurement of the muon p_{T} with an accuracy better than 10% for p_{T} values around 10 GeV to satisfy the trigger performance requirements. Since both the position and the angle (direction) of the segments are used, the p_{T} accuracy requirement translates to a required resolution of $\sigma_r \leq 1\,\mathrm{mm}$ and $\sigma_\theta \leq 1\,\mathrm{mrad}$ in the MDT segment position and angle respectively.

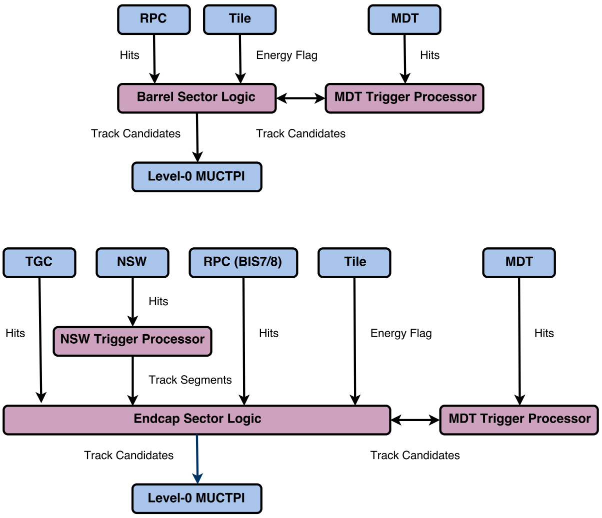
The performance of the MDT trigger algorithm has been studied with ATLAS simulated data by applying the MDT trigger on top of the RPC/TGC trigger emulation. The MDT segments that are matched with the input trigger candidates are used to calculate the candidates p_{T} using the recipe mentioned above. The single muon trigger efficiency has been studied with single muon events covering the whole η-ϕ range of the ATLAS muon trigger ($|\eta| \leq 2.4$). Figure 4a shows the efficiency for 20 GeV threshold as a function of the muon p_{T}. The MDT trigger provides an improved selectivity for the muons with p_{T} around the threshold, while keeping a high plateau efficiency[1].

Complementary to the trigger functionality, the MDT TP will also provide the data acquisition (DAQ) path for the MDT data and will also be responsible for transmitting clock and configuration data to the MDT front-end electronics. The interface with the ATLAS DAQ is realised via the FELIX system [7].

[1]The maximum plateau efficiency is defined by the RPC/TGC trigger



(a)



(b)

Figure 2: The upgrade of the ATLAS Muon Trigger system: (a) Cross-section of an ATLAS Muon system quadrant showing the trigger coincidences applied per region, (b) Block diagram of the upgraded first-level ATLAS Muon Trigger System [5]

3 The Legendre transform algorithm for MDT segment reconstruction

The hit information for each MDT tube is composed of the tube id and a drift radius that corresponds to the drift time of the earliest ionisation electron. To reconstruct a segment one

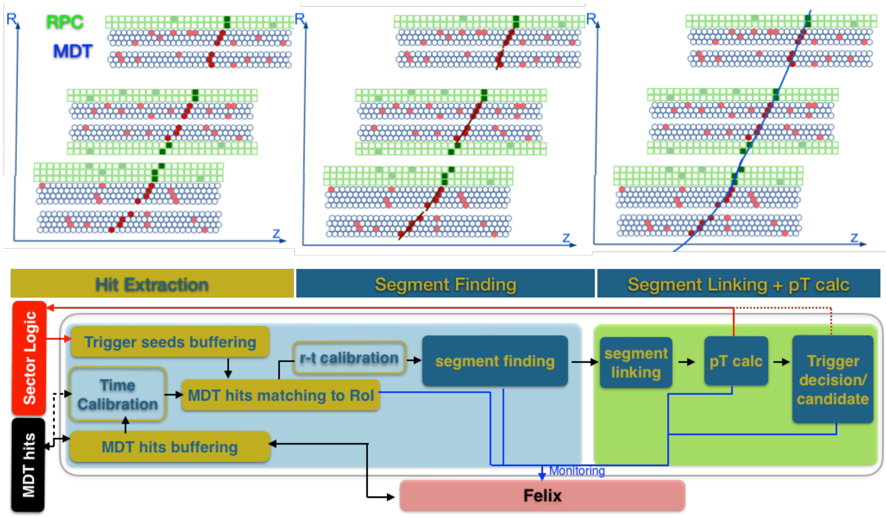
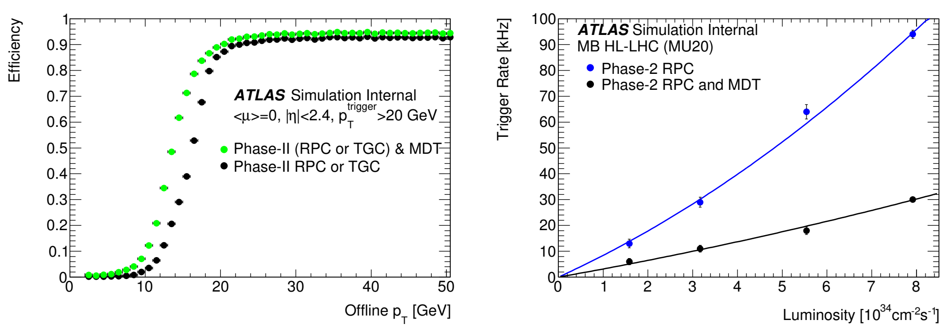


Figure 3: Diagram of the main functionalities carried out in the MDT TP.



(a) (b)

Figure 4: Single muon trigger efficiency and rate before and after the application of the MDT trigger [5]: (a) Efficiency as a function of the p_{T}, (b) Expected single muon trigger rate as a function of luminosity

needs to find the straight line that is common tangent to all the drift circles (hits) that were generated by the same particle. We propose the use of a novel algorithm, called the Legendre Transform (LT) [6], for segment reconstruction in the MDT to be used for the MDT trigger in ATLAS. The algorithm properties make it particularly convenient for performing fast segment finding using pattern recognition in the MDT chambers, since

- The exact position of the hits along the perimeter of the drift circle does not need to be calculated
- The processing time does is independent of the number of hits since it can be easily parallelised in an FPGA implementation as described in sec.4.2.

3.1 Principle

The implementation of the LT for segment finding is based on the transform of each MDT tube position, in the global coordinate system of ATLAS, and drift radius, $(R_0, z_0, r_{\text{drift}})$, to the Legendre space in polar coordinates (r, θ) [6]. The basic principle of the LT is described in Fig. 5, and uses the transformation to polar coordinates in eq. (1). Each drift circle is represented by two lines in the Legendre space corresponding to its concave and convex parts, respectively. Each (r, θ) point in the Legendre space represents a line in the Cartesian coordinate system, tangent to the corresponding drift circle. When the LT is applied on all the drift circles of one chamber, the most populated (r, θ) bin of the Legendre space will represent the tangent line that is common for the majority of the drift circles.

$$r = z_0 \cos\theta + R_0 \sin\theta \pm r_{\text{drift}}. \tag{1}$$

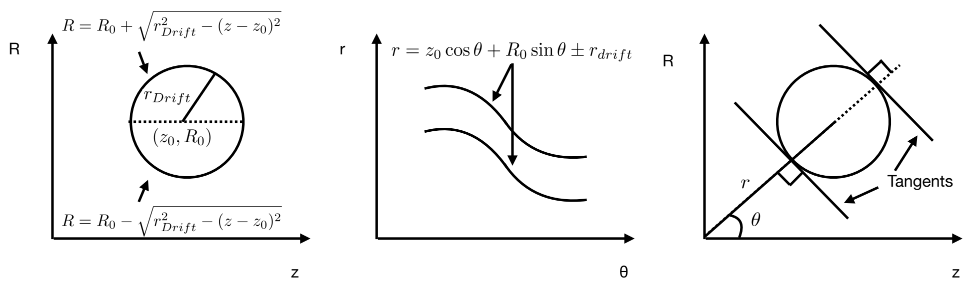


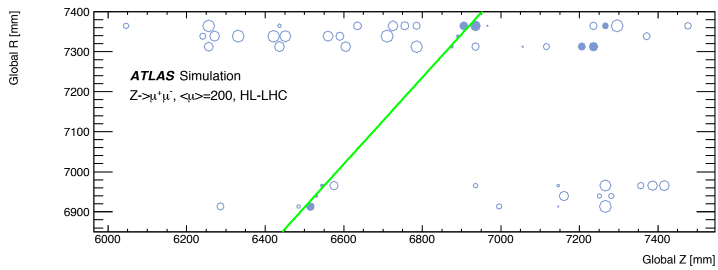
Figure 5: Basic principle of the LT algorithm for calculating tangent lines to a circle

Figure 6 shows a typical event display for one MDT station using ATLAS simulation with emulated HL-LHC conditions. The drift circles in the global $z-R$ coordinate system are presented in Fig. 6a. R is the cylindrical radius of the hits with respect to the axis that passes through the middle of the sector in ϕ and z goes along the beam axis. This is a convenient coordinate system for the segment finding and track fitting in a single sector since the R axis is common for all stations within the same sector. The filled drift circles correspond to hits that are attached to offline reconstructed segments while the empty ones are just random hits. The Legendre transformations of the drift circles that have been matched to the trigger seed are shown in Fig. 6b. The (r, θ) bin with maximum occupancy defines the slope and intercept of the most popular tangent line. Since the number of entries in the maximum bin is 6, this line is tangent to 6 circles which can be confirmed from the left plot.

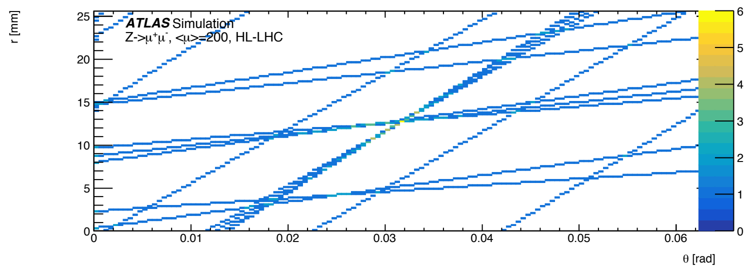
3.2 Segment finding and reconstruction performance

The performance of the algorithm has been studied in simulation by comparing with ATLAS offline reconstruction. There are several parameters of the algorithm that require proper tuning to maximise the performance in terms of efficiency and resolution. The segment position and angle accuracy is limited by the r, θ resolution of the Legendre space. The granularity of the Legendre space has been studied using simulations and a bin size of 0.2 mm and 0.5 mrad for r and θ has been chosen to maximise the performance.

One additional parameter that affects the segment finding efficiency of the algorithm is the size of the Legendre space. In order to save processing time and resources the search in the Legendre space must be confined within a small range of values along r and θ. The



(a)



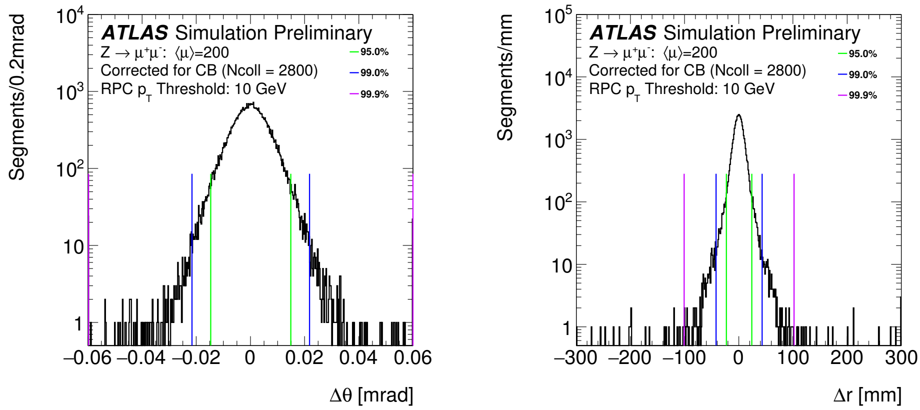
(b)

Figure 6: Event display in one MDT chamber at simulated HL-LHC conditions: (a) Drift circles in the ATLAS z-R coordinate system, (b) Representation of the drift circles in the Legendre space using polar coordinates

trigger seed (received from the SL) position and direction are thus used as a reference and the Legendre space for the segment finding is extended around the reference r and θ. However, since the seed angle and position resolution is rather moderate, the r and θ ranges must be sufficiently large such that the common tangent line bin is always within range. The proper dimensions of the Legendre space have been studied by comparing the reference r and θ with the MDT segment r and θ coordinates for all the different regions of the muon spectrometer and MDT chamber types. An example is shown in Fig. 7 for all large MDT sectors in the inner layer of the barrel region. The difference in r and θ between seed and MDT segments is plotted along with the axes ranges that ensure a specific segment finding efficiency[2]. We have concluded that a Legendre space of ± 64 bins of 0.5 mrad along θ and ± 64 bins of 0.2 mm along r are sufficient to ensure that the tangent line is reconstructed in more than 95% of the cases across all the MDT chambers.

The segment angle and position accuracy of the LT algorithm, has been evaluated using simulation events with single muons. To estimate the accuracy in the segment reconstruction using the LT algorithm, the position and angle (polar angle θ with respect the ATLAS global z-axis) between the reconstructed segment and the segment from the offline ATLAS reconstruction are compared. Figure 8 shows the segment position and angle difference distributions. It can be seen that most of the reconstructed segments agree very well with the result of the offline reconstruction while a small percentage ($< 5\%$) sits on the tails of the

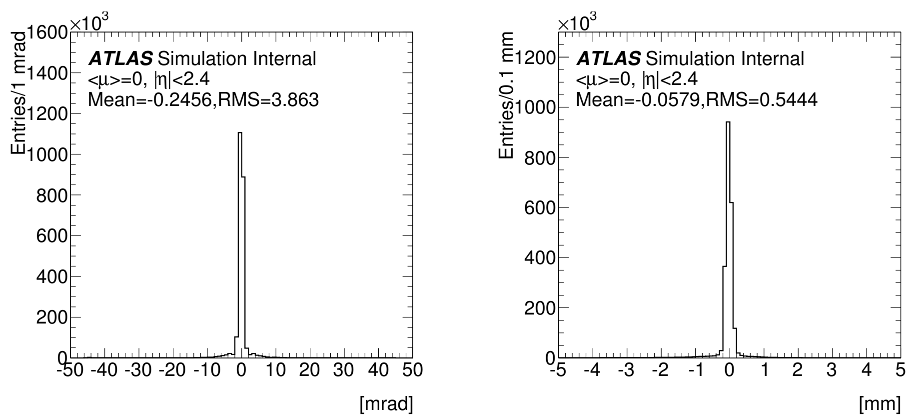
[2]By efficiency we mean the probability of the actual MDT segment being within the limits if the Legendre space axes



(a) (b)

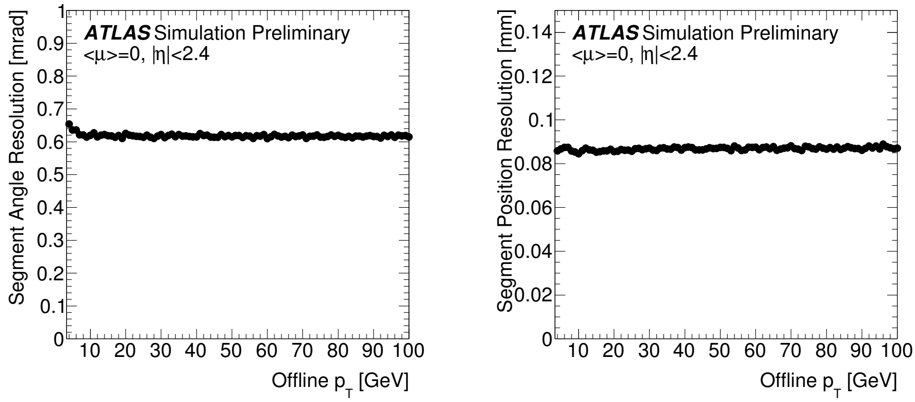
Figure 7: Difference in angle (a) and position (b) betteween the segment reconstructed using the seed information and the matched offline reconstructed MDT segment in the same station.

distributions. The position and angle resolution of the reconstructed segments can be estimated by fitting the core distribution corresponding to 95% of the segments with a gaussian function. The σ of the fit is plotted as a function of the offline muon p_{T} in p_{T} slices of 1 GeV in Fig. 9. The LT algorithm is able to reconstruct segments with an accuracy of ~ 0.6 mrad in angle and ~ 90 μm in position which is stable along the full p_{T} range studied [4, 100 GeV].



(a) (b)

Figure 8: Difference between the angle (a) and position (b) of the segment reconstructed with the LT and the corresponding segment from offline reconstruction.



(a) (b)

Figure 9: Segment reconstruction accuracy as a function of the muon p_{T}: (a) Angle resolution, (b) Position resolution

4 Hardware implementation

4.1 MDT Trigger Processor ATCA blade

The MDT trigger system is partitioned into 64 processing elements implemented in Advanced Telecommunication Computing Architecture (ATCA) carrier boards, each handling one sector (out of 16), one side (A/C), and one region (barrel/endcap). Figure 10 illustrates an ATCA blade which handles one out of the 64 sectors. A total of 144 fibre receivers and transmitters are needed for interfacing with the MDT frontend and the other elements of the ATLAS trigger and DAQ system.

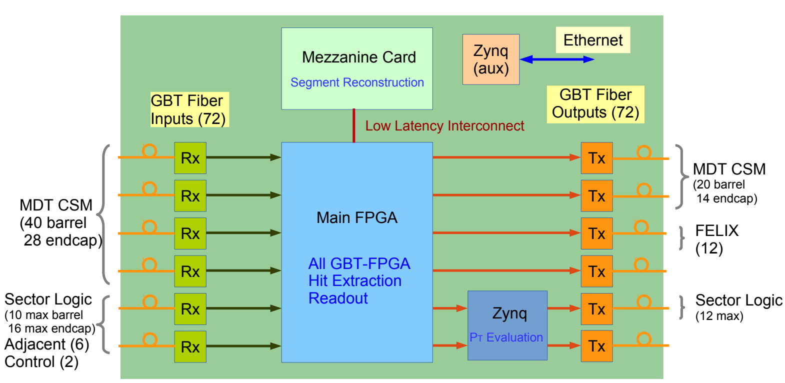


Figure 10: Conceptual design of the MDT TP ATCA blade.

The blade contains one Xilinx UltraScale FPGA, which handles the receipt of the MDT hits, receipt of the SL trigger candidates, hit extraction, calibration, transmission of hits to the mezzanine board, receipt of the segment data from the mezzanine board and transmission of the final MDT trigger candidates to the SL. The segment identification and reconstruction is performed in a FPGA housed on a mezzanine board while the p_T calculation is performed in a Xilinx Zynq device.

4.2 Legendre Segment finder FPGA implementation

The hardware implementation of the segment reconstruction with Legendre transform fits the resources of modern large FPGAs. During the initialisation stage (Fig. 11a), the sin and cos values are copied from a pre-computed Look-Up Table (LUT) to local registers for a range of track angles around the trigger seed angle. The LT value from equation (1) is calculated simultaneously for all 128 θ values using DSP blocks in the FPGA fabric. The output of each calculation is an r value and a bit to signal if the value is in range or not. Each r value (for each of 128 columns in parallel) is used to increment a histogram bin (Fig. 11b), while simultaneously keeping a record of the location of the most populated bin. Finally, a binary search is performed along the 128 columns to find the most populated bin that defines the output segment. This consists of an offset in the coordinate of the beam axis plus an angle, as well as the contents of the most populated bin, which can be utilised as a segment quality variable.

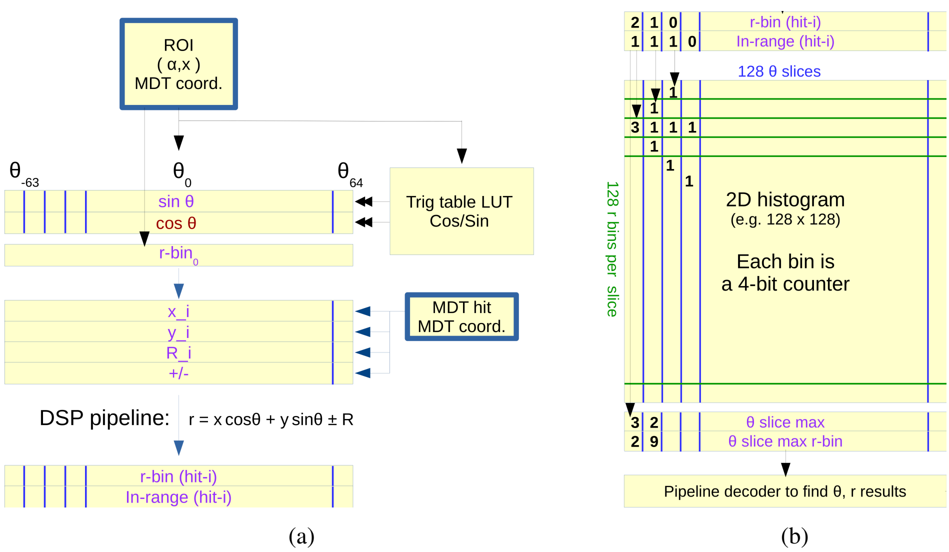


Figure 11: Block diagram of the Legendre transgorm FPGA implementation: (a) Initialization, (b) Histogram filling per hit

This approach is relatively expensive in FPGA resources, requiring for the dimensions given above $128 \times 128 \times 4 = 64$k registers for one Legendre histogram. An estimation of the resource usage in an actual implementation in an UltraScale FPGA is summarised in Table 1. However, modern FPGAs can easily accommodate several instances of this design in a single device. In terms of latency we anticipate that the logic described above can operate comfortably at the 360 MHz pipeline speed. The segment finding is performed within 78 ns which is a small fraction of the the overall MDT TP latency which is estimated to be $\sim 1.4\,\mu$s (after the arrival of the last MDT hit) as can be seen in Table 2.

Table 1: FPGA resource usage for the Legendre transform segment finder

Mezzanine FPGA (1 out of 3)				
	Number	**LUTs**	**Regs**	**BRAMs**
Legendre Engine	3	96,500	104,500	275
Total		289,000	313,500	825
XKCU115		663,360	1,326,700	4,320
%Use		44%	24%	19%

Table 2: Latency breakdown for the MDT trigger processor with the Legendre transform segment finder

Contents	Latency [μs]
Earliest MDT hit signal arrival	0.609
Sector logic track candidate arrival	1.785
Latest MDT hit signal arrival	2.358
Decoding and domain crossing	2.458
Buffering	3.424
Hit extraction	3.432
Data transfer to the mezzanine cards	3.457
Segment reconstruction	3.510
Conversion to the detector coordinates	3.535
Data transfer to the main board	3.560
Transverse momentum evaluation and selection	3.635
Optical link to the Sector Logic (10 m)	3.810

5 Conclusions

A segment finding algorithm based on the LT is proposed to be used in the MDT TP that will be included in the upgraded ATLAS first-level muon trigger for HL-LHC. The studies of the algorithm demonstrate excellent performance fulfilling the muon trigger requirements for HL-LHC. The LT segment finder has been successfully implemented in a modern Ultrascale FPGA. Although it occupies a significant amount of the FPGA resources the parallelisation of the algorithm's processing steps results in a very low latency that does not scale with the number of MDT hits that have to be processed.

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