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# Development of a pattern-matching algorithm for the L0Muon Barrel Trigger for the muon spectrometer of the ATLAS experiment(*)

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**Summary.** — The ATLAS Level-0 Muon trigger for the Phase-2 upgrade will use powerful Field-Programmable Gate Arrays (FPGAs) to perform fast trigger algorithms. In particular, the Barrel Sector Logic board will receive data from the RPC detectors and the Tile Calorimeter and provide muon candidates within a latency of a few hundred nanoseconds. Different approaches, such as geometrical methods, neural networks, and pattern matching, can be used to implement the trigger algorithms in the FPGA firmware. We discuss the development and optimization of a pattern-matching algorithm and present the preliminary results of our study.

## 1. – Introduction

During the Long Shutdown 3 (LS3), the Large Hadron Collider (LHC) at CERN will undergo several upgrades in preparation for the High-Luminosity (HL-LHC) phase [1]. HL-LHC will provide pp collisions at 14 TeV with peak luminosity up to $7 \cdot 10^{34}$ cm$^{-2}$s$^{-1}$, a factor of five beyond the original design, and integrated luminosity up to 4 ab$^{-1}$, a factor of ten higher than the LHC one.

The ATLAS experiment [2] will largely benefit from this collider setup but upgrades of the ATLAS detector are needed. For the muon system, the renewal for the so-called Phase-2 includes the installation of new particle detectors in both the barrel and end-cap regions, the replacement of both the on-detector and off-detector electronics, and the upgrade of the Trigger and Data Acquisition system. All these interventions are aimed at making the ATLAS detector able to cope with a pile-up, *i.e.* the average number of collisions per bunch crossing, of $\sim$200 while maintaining, or improving, its performance at the current lower pile-up (about 60).

## 2. – The L0Muon Barrel Trigger

The current ATLAS Level-1 Trigger system (L1) will be reorganized into a new hardware-based Level-0 Trigger (L0) [3]. The future L0 Trigger subsystem used for triggering muons in the barrel region, the L0Muon Barrel Trigger, in particular, will exploit

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Fig. 1. – Prototype of the off-detector boards implementing the Sector Logic (SL) for the L0Muon Barrel Trigger. Each board consists of a commercial board with one FPGA, where both the SL and the readout logic are implemented.

additional Resistive Plate Chambers (RPC) for improving the trigger acceptance (from 75% to ∼95%) and powerful Field-Programmable Gate Arrays (FPGAs) to perform the trigger algorithm. The Xilinx Virtex Ultrascale+ XCVU13P has been proposed. The Barrel Sector Logic (SL) boards (fig. 1), where the FPGAs are mounted, will receive data from RPC detectors and the Tile Calorimeter, use them to elaborate the trigger decision, and provide muon candidates within a latency of about 400 nanoseconds.

The new geometry of the ATLAS muon spectrometer [4], where three new Barrel-Inner RPC layers in the barrel region are added to the six legacy Barrel-Medium1, Barrel-Medium2, and Barrel-Outer RPC layers (2 layers each), will not only provide higher geometrical acceptance to the L0Muon, but also permit the development of different trigger algorithms. The redundancy of RPC planes (fig. 2), indeed, allows us to explore a wider set of coincidences, as shown in fig. 3. In a preparatory step, the nine RPC

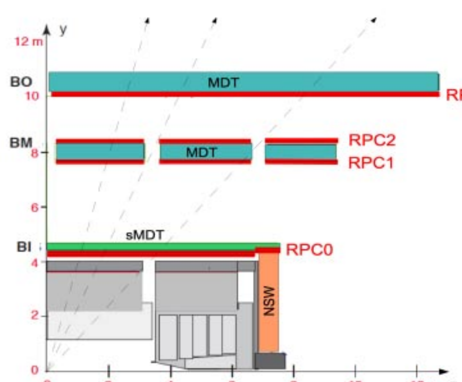


Fig. 2. – With the Phase-2 upgrade, the ATLAS muon spectrometer [4] will host a total of 9 RPC layers: 2 layers (RPC3) in the Barrel-Outer (BO) stations, 2+2 layers (RPC2+RPC1) in the Barrel-Medium (BM) stations, and 3 additional layers (RPC0) in the new Barrel-Inner (BI) station. Part of the BI Monitored Drift Tubes (MDTs) will be replaced with smaller MDT tubes (sMDT) to host the new RPC0 chambers.

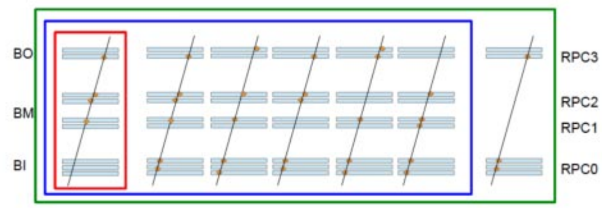


Fig. 3. – Sketch of all the possible coincidences used in the L0Muon Barrel Trigger for the ATLAS Phase-2 [5]. The small red box shows the coincidence scheme, BM1-BM2-BO, used since Run 1, in the new Phase-2 configuration (acceptance ∼70%). The intermediate blue box, instead, shows all 3/4 coincidences provided by the installation of the BI RPC chambers (acceptance ∼90%). Finally, the largest green box displays 3/4+BI-BO coincidences that can be used to push the acceptance of the L0Muon up to the ∼95%.

detector layers are reduced to four by applying an OR on RPC doublets and a 2/3 majority on the BI triplet. After this step, several approaches have been developed for the implementation of the trigger algorithm:

- *Geometrical methods* [5]: hits on the BI stations are used as seeds to search for hits in the next RPC stations within fixed and pre-computed geometrical windows. Whenever a new hit is met, the algorithm opens a new window in the following stations, until BO station is reached. The set of all the identified hits defines a pattern, the muon candidate track. The size of these windows is strictly connected to the muon transverse momentum threshold since the bending effect of the toroidal magnetic field in the muon spectrometer.

- *Machine Learning* [6]: hits from RPC are transformed into images, where high transverse momentum muons are expected to show as vertical or slightly-sloped segments, and processed by a machine learning algorithm. A neural network evaluates the momentum from the curvature of the identified muon tracks. The output of the network is the set of muon candidates.

- *Pattern-Matching*: RPC hits are compared with look-up tables of pre-computed patterns extracted from Monte Carlo simulations and ATLAS reconstruction algorithms.

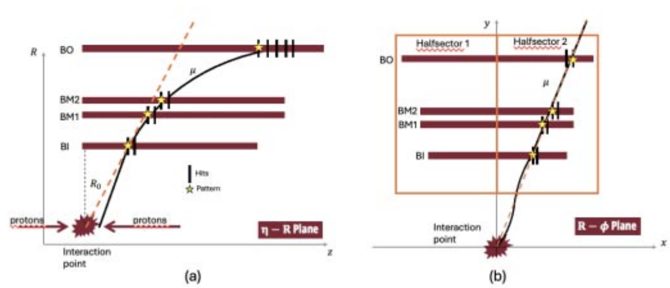


Fig. 4. – Representation of the *eta* (a) and *phi patterns* (b) extracted from a muon track.

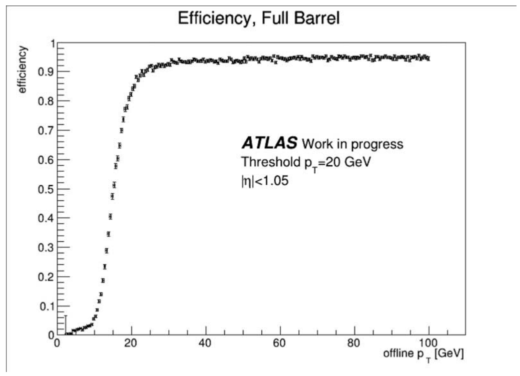


Fig. 5. – Efficiency curve obtained with the proposed pattern-matching algorithm for the ATLAS L0Muon Barrel Trigger. A fixed threshold of 20 GeV is applied. Events that pass the trigger selection are those matching with at least one *eta pattern* with momentum above the threshold and with one *phi pattern*. The matching with the *phi pattern* is used to suppress noise and undesired matches of low pt muons with high momentum patterns.

## 3. – Pattern-Matching Algorithm

The idea behind a pattern-matching algorithm is straightforward and consists of having a list of fixed, pre-computed patterns, stored in the FPGA look-up table units (LUT), to be compared with the full set of incoming RPC data. The decision of the trigger system is based on the information associated to those patterns which exhibit the maximum agreement with the data.

To construct unbiased tables of patterns, we used single-muon Monte Carlo samples, with uniform momentum distribution in [0,50] GeV, processed through a 100%-efficiency simulation of the interaction of the particles with the ATLAS detectors, and finally handled by the ATLAS reconstruction algorithms. Hits in the BI RPC chambers, not included in the current simulation of the ATLAS detector, are obtained via ad-hoc digitization of Geant4 hits in the innermost layers of MDTs.

The first step is the search for the *eta pattern* (in the longitudinal plane)([1]), relevant for the measurement of the transverse momentum of the muon: starting from the representation of the event in the physical space, per each of the four RPC stations, we select the hit that is the closest to the line connecting the nominal interaction point with the point where the muon enters in the spectrometer (fig. 4(a)), thus, extracting a four-hits pattern. In this way straight patterns will represent high transverse momentum muons, while curved patterns will represent low momentum muons. The second step is the extraction of the *phi pattern*, in the transverse plane: the *phi pattern* is simply obtained by considering the closest phi strips to the previously identified *eta pattern* (fig. 4(b)). Each pattern is then associated with momentum, charge, and additional information that will be used by the algorithm to take the final decision.

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([1]) The distinction between *eta* and *phi patterns* relies on the kind of strips considered to create such patterns. *Eta patterns* are made from eta strips, devoted to the measurement of the $\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$ coordinate, being $\theta$ the angle to the beamline in the longitudinal plane. In contrast, *phi patterns* are constructed from phi strips devoted to the measurement of the angle $\phi$ in the transverse plane, with respect to the LHC ring plane.

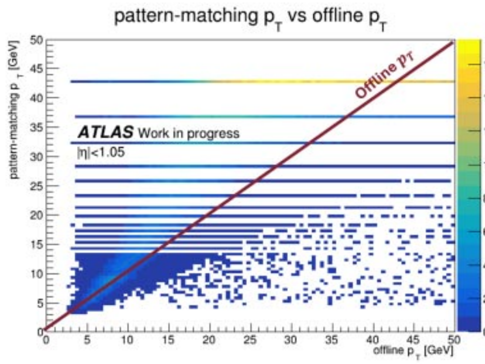


Fig. 6. – Comparison of the pattern transverse momentum with the offline transverse momentum for ATLAS reconstruction algorithms. Notice that the pattern momentum distribution is binned accordingly to the L0Muon guidelines, requiring a uniform binning on the sagitta measurement, which is proportional to $1/p_T$.

## 4. – Pattern-matching results

Preliminary performance of the trigger algorithm running on the different Sector Logic boards were studied using a second, independent, single-muon Monte Carlo sample. Figure 5 shows the efficiency curve that we obtained with a fixed threshold of 20 GeV. This curve exhibits a high-efficiency plateau, about 95%, for muons with momentum above the threshold, and a steep rise in the [10,20] GeV range. A few percent efficiency is observed for low momentum muons below 10 GeV, indicating that the requirement of both an *eta pattern* and a *phi pattern* for the same candidate is not enough to fully suppress the matching of high-momentum patterns with low-momentum muons in BI-BM1-BM2 coincidences. Further studies are needed to mitigate this effect. Nevertheless, good momentum resolution on the selected muons and good coverage along all the barrel region are reached, as shown in figs. 6 and 7.

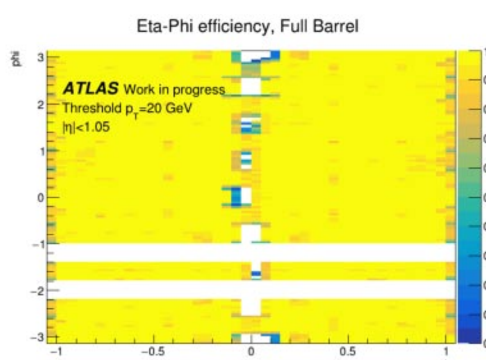


Fig. 7. – Plateau efficiency of the pattern-matching algorithm along the full barrel of the ATLAS detector for the Phase-2 upgrade. The white horizontal bands correspond to those regions of the detector for which the final phase-2 layout was not available yet.

Graph | **Table**

| Resource | Utilization | Available | Utilization % |
|---|---|---|---|
| LUT | 41422 | 1728000 | 2.40 |
| FF | 119539 | 3456000 | 3.46 |
| IO | 1 | 448 | 0.22 |
| BUFG | 1 | 1344 | 0.07 |

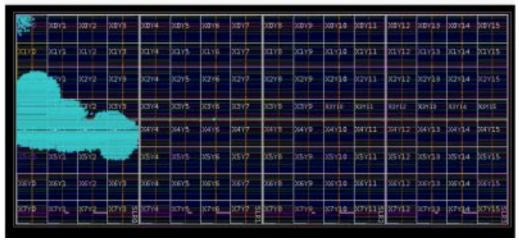

Fig. 8. – Occupancy of the FPGA resources during the preliminary studies for the pattern-matching algorithm. This test only includes the matching logic between incoming data and patterns. The priority encoder selecting the best muon candidate is not included.

Preliminary studies on FPGA showed that the selected FPGA model is able to handle $\mathcal{O}(1.5{\cdot}10^5)$ patterns and that few percent of the total FPGA LUTs and Flip-Flops (FF) are needed for the matching-algorithm between data and patterns (fig. 8).

## 5. – Conclusion

The idea and expected performance of a pattern-matching algorithm for the ATLAS upgrade for Phase-2 were presented. This is the first time in the ATLAS experiment that a pattern-matching algorithm has been considered for the trigger system in the barrel region of the muon spectrometer: preliminary studies prove the potentiality of this algorithm in terms of physical performance. Indeed, although the algorithm is still under development, these results prove that this pattern-matching algorithm might be a valid candidate for the L0Muon Barrel trigger algorithm for Phase-2. Recently the implementation of the full algorithm on the Sector Logic FPGA started. Further studies on FPGA will establish if this algorithm is able to fulfill the strict latency requirements for the HL-LHC.

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