Study of ATLAS TRT performance with GRID and supercomputers.

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One of the most important studies dedicated to be solved for ATLAS physical analysis is a reconstruction of proton-proton events with large number of interactions in Transition Radiation Tracker. Paper includes Transition Radiation Tracker performance results obtained with the usage of the ATLAS GRID and Kurchatov Institute's Data Processing Center including Tier-1 grid site and supercomputer as well as analysis of CPU efficiency during these studies.

1. Introduction

After the early success in discovering a new particle consistent with the long awaited Higgs boson, the Large Hadron Collider (LHC) [1] experiments have started the precision measurements and they are ready for further discoveries that will be made possible by much higher LHC collision rates from spring 2015. ATLAS, one of the four experiments at the LHC, is leading a computing evolution program to evolve their software and computing model to make the best possible usage of available resources, including supercomputers [2]. A proper understanding of the detectors performances at high occupancy condition is important for many on-going physics analyses. The ATLAS Transition Radiation Tracker (TRT) [3-5] is one of these detectors.

TRT is a large straw tube tracking system that is the outermost of the three subsystems of the ATLAS Inner Detector (ID). TRT contributes significantly to the resolution for high-pT tracks in the ID providing excellent particle identification capabilities and electron-pion separation. ATLAS experiment is using Worldwide LHC Computing system (WLCG) GRID [6]. WLCG is a global collaboration of computer centers and it provides seamless access to computing resources, which include data storage capacity, processing power, sensors, visualization tools and more. WLCG resources are fully utilized and it is important to integrate opportunistic computing resources such as supercomputers, commercial and academic clouds no to curtail the range and precision of physics studies. One of the most important studies to be solved on a supercomputer is the reconstruction of proton-proton events with large number of interactions in TRT. These studies are made for ATLAS TRT Software (SW) group. It becomes clear that high-performance computing contributions become important and valuable. An example of a very successful approach is Kurchatov Institute's Data Processing Center including Tier-1 GRID site and supercomputer. The presented paper includes TRT performance results obtained with the usage of the ATLAS GRID and "Kurchatov" supercomputer as well as analysis of CPU efficiency during these studies.

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2. ATLAS tracking detector system

The ATLAS detector at the LHC is a general-purpose detector, designed to make precision measurements of known physics processes and to probe new physics at the energy frontier of the LHC. Tracking detector system embedded in a 2 T axial magnetic field produced by a solenoid is placed in the center of the detector. It is designed to enable the precision measurement of charged particle trajectories in the environment of numerous tracks and is called the Inner detector (ID). The Inner detector consists of a Silicon Pixel Detector, surrounded by a Silicon Microstrip Detector (SCT) and a straw-tube detector called the Transition Radiation Tracker. Pixel detector mainly contribute to the accurate measurement of vertices, SCT measures precisely the particle momenta, TRT eases the pattern recognition with its very large number of close hits (extensions) and contributes to electron identification. Hits recorded in individual detector elements are used to reconstruct the trajectories of charged particles inside the tracker and ultimately to estimate their kinematic parameters.

First works on transition radiation detectors development started in National Research Nuclear University MEPhI under prof. B. Dolgoshein's guidance in the early 1970s in Moscow [7-9]. MEPhI group proposed a novel concept of Transition Radiation Tracker for experiments at future LHC colliders in 1989, took a leading role in the installation into the ATLAS detector and continue maintenance of this detector during the whole LHC operation.

The TRT has enormous amount of the readout channels: 350,848 individual channels. The partial resolution is around 130 micrometers. It consists of three parts: barrel and two end-caps (A and C wheels). The TRT is made of thin-walled drift tubes (straws). The straws work in proportional mode with 1.5 kV potential in the straw wall with respect to the wire that is held at ground. The space between the straws is filled with radiator material. The TR photons (soft X-rays) emitted in the radiator are absorbed in the gas inside the straw tube. The TRT designed such a way that particle crosses in average 30 straws in the TRT acceptance range. The TRT operates as a drift chamber: when a charged particle traverses the straw, it ionizes the gas, creating about 5-6 primary ionization clusters per mm of path length. The electrons then drift towards the wire and cascade in the strong electric field very close to the wire (Figure 1). The signal on each wire is amplified, shaped and discriminated against adjustable thresholds [10]. A low threshold (LT) is set at about 250-300 eV and a high threshold (HT) is set at about 6-7 KeV. The low threshold is used to measure an electron drift-time for the tracking and the high-threshold is used to identify a large energy deposits from absorbed TR photons for particle identification. Particle separation is based on probabilities to exceed high threshold, which is different for electrons that produce TR and other particles with gamma factors below 1000. High threshold is optimized to obtain the best electron-pion separation. Precise measurement of particle trajectories is a fundamental part of physics analysis.

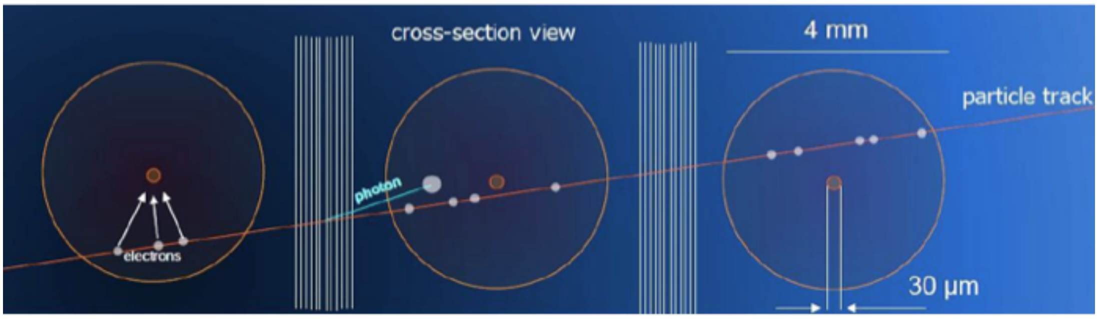


Figure 1. The scheme illustrating charged particle traverses the TRT straws

3. TRT Software studies and GRID elaboration

High-energy physics data are organized as events or particle collisions. Computer power is used for detectors operating, physics simulations, events reconstruction in detectors and finally events selection. During Run 1 in 2011-2012 ATLAS has collected already incredible amount of data (about 30 fb^{-1} for physical analyzes). A lot of work in the ATLAS TRT software (SW) group was done using tremendous amount of CPU. Study of the TRT performance at high occupancy is one of them. It was actually great challenge for computers since events reconstruction in TRT require reconstruction of each hit on track for events with high number of simultaneous interactions per bunch crossing <μ>. Good operation of the TRT detector decreases tracking uncertainty. It is crucial to understand the future work of the TRT detector with higher energies and <μ> during Run 2 in 2015-2018. Studies demonstrated a good agreement between data and simulation. Figure 2 shows the occupancy as function of <μ> for the total TRT detector. Here occupancy is defined as the probability to have a low level (low threshold) hit within the 75 ns readout window. For each region, the occupancy is calculated as the number of straws with a low level discriminator fired during the 75 ns readout window divided by the total number of straws in the region. The plot shows that the simulation describes well the dependence of the occupancy on the pile-up. The occupancy increases linearly from about 24% at <μ> =45 to 35% at <μ>=70. The <μ> values expected for Run 2 are about 25-40 (assuming 25 ns LHC bunch spacing) and it is expected that there is no significant performance loss in this pile-up range in spite of a worsening of the TRT hit residual in higher occupancy events. The TRT demonstrates good performance at occupancies up to 0.5 for proton-proton running.

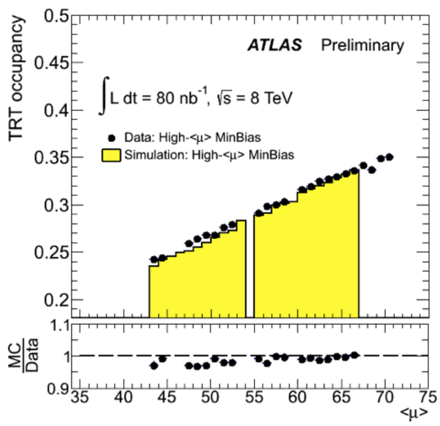
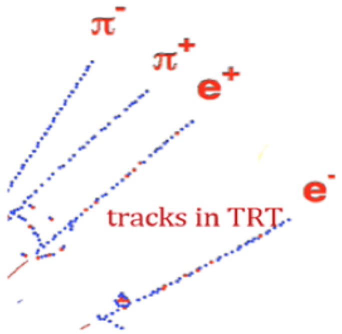


Figure 2. TRT straw occupancy as a function of <μ> in the total TRT for 2012 runs. Data (solid circles) and simulation (filled histograms)[11]

The main goal of TRT particle identification (PID) task is to separate electrons from pions traveling through the detector's volume by using a lot of tracks information available. Figure 3 illustrating the structure of such tracks: while electron tracks contain a lot of HT hits, pion tracks contain much more LT hits and very few HT hits because of pion's mass is much higher that electron's mass.

Figure 3. Low level (blue) and High level (red) hits on the particle track inside TRT detector for electrons and pions



TRT PID tool [12] must be calibrated before obtaining the best separation power while collecting the data. Measurements the gamma dependencies of High Threshold Probabilities (pHT) are needed to be included in such kind of tools. All available physical effects, which could help to improve the separation power and performance of the tool, should be firstly studied. In order to do this a lot of different Monte Carlo samples that reproduce the required conditions should be produced. This is a very resource-intensive computational problem as far as simulation of the realistic detector response takes a lot of CPU time.

Table 1. Comparison between LHC physics during Run 1 and Run 2.

	Run 1	Run 2
Energy [TeV]	7-8	13-14
Luminosity [fb^{-1}]	30 (2011-2012)	150-300 (2015-2018)
Number of bunches	1400	2500-2800
Average number of interactions $<\mu>$	30	40
Bunch spacing [ns]	50	25

To address an unprecedented multi-petabyte data processing challenge, the LHC collaborations are relying on the computational GRID infrastructure consisting of hundreds of distributed computing centers deployed by the GRID. Using the massive data processing power of the GRID, more than 10 000 scientists analyze LHC data in search for physics discoveries. As far as GRID is allowing us to perform parallel calculations, the TRT performance at high occupancy and the TRT PID studies on the GRID are running much faster than by usual AFS computing system.

To understand the elaboration of GRID it is useful to trace the LHC physics evolution. Table 1 demonstrates comparison between the LHC ATLAS physics during Run 1 and Run 2. These major parameters such as energy, number of bunches, luminosity will increase at least by factor 2 or even larger, while time between two bunches will decrease in 2 times. All together it will require development of services and facilities. Supercomputers linked to the GRID system could significantly contribute to GRID performance and both technical and physical tests should be accurately held to validate these implementations. Kurchatov Institute's Data Processing Center including Tier-1 GRID site and supercomputer are used to perform these tests.

4. Kurchatov Institute computing facilities

The Tier-1 facility at Kurchatov Institute (NRC-KI) in Moscow is a part of WLCG collaboration. Sophisticated Workload Management Systems (WMS) are used to manage the data processing, simulations and analysis.

One of the scalable WMS developed for high-energy physics is PanDA. The ATLAS experiment uses PanDA for managing the workflow for all data processing on the WLCG. Through PanDA, ATLAS physicists see a single computing facility, even though the data centers are physically scattered all over the world. Initially PanDA has been used only on the facilities managed by WLCG. Support for High Performance Computers (HPC) expands the potential user community for PanDA and also, in the near term, allows LHC experiments to run jobs on HPC facilities, so supplementary CPU resources can be acquired.

In 2014 a pioneering work to develop a large scale data- and task-management system for federated heterogeneous resources has been started at the National Research Centre "Kurchatov Institute" (NRC KI, Moscow). As a large part of this work, the portal which allows payload submission to heterogeneous computing infrastructure was designed, developed and deployed. It combines Tier-1, Cloud-infrastructure, and a supercomputer at the Kurchatov Institute. This portal is aimed to provide a common interface to submit tasks to GRID sites, commercial and academic clouds and supercomputers. Integration of Tier-1 and the supercomputer has allowed to notably increase total CPU capacity available for LHC experiments. As a basis technology PanDA workload management system has been chosen.

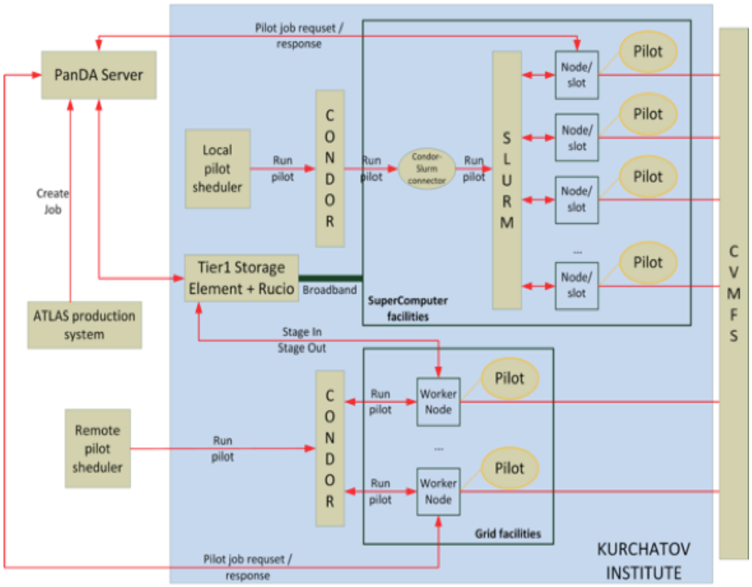
The following resources were integrated for the portal at NRC KI:

- The supercomputing facilities at Kurchatov Centre for Collective Usage which include high performance cluster with peak performance of 122.9 TFLOPS. It operates since September 2011 and consists of 1280 nodes each with 2 8-core CPUs (10240 cores total) interconnected with high throughput InfiniBand DDR network. Its total RAM is 20.5 TB and local data storage has 144 Tb in Lustre 2.0 parallel file system. Nodes run CentOS Linux and SLURM is used as a batch system and scheduler.
- One of the largest Russian WLCG Tier-1 centers at NRC KI: it provides more than 8000 CPU slots, 6.3 PB of disk-based storage and 7.4 PB of tapes. The Tier-1 facility processes, simulates and stores up to 10% of total data obtained from ALICE, ATLAS and LHCb experiments.
- OpenStack based Cloud platform having performance 1.5 TFLOPS and providing 16 nodes, 256 cores, 512 Gb RAM, 60 Tb at storage system and InfiniBand connectivity.

ATLAS is one of the HEP experiments supported by this portal. In the main ATLAS runs single-core jobs and uses specialized software to process and analyze data that comes from detector. This allows reusing a lot of already existing components, however, we still had to perform a considerable work to integrate different computing resources, such as supercomputer and GRID facilities.

Portal diagram and workflow, which supports ATLAS jobs at GRID Tier-1 center and supercomputer at NRC KI, is given at figure 4. In this scheme the portal interacts with the central PanDA server a general WMS service at CERN, where queues for NRC KI are defined and bound to the GRID and the supercomputer resources at NRC KI. Special applications on client side are used by physicists to submit ATLAS jobs (Prun, Pathena). GRID storage element and ATLAS Distributed Data Management system are used for data manipulation.

Figure 4. Portal working scheme supporting ATLAS jobs at GRID and supercomputer resources at NRC KI



Pilot jobs are used in PanDA system for acquisition of processing resources. Workload jobs are assigned to successfully activate and validate pilots by the PanDA server based on brokerage criteria. Default ATLAS pilot scheduler supports HTCondor batch system. Additional component to translate jobs to SLURM for the supercomputer was developed. In the classical approach each pilot submitting to the batch system slot usually associated with one core. In this case pilots are running locally at the worker nodes of GRID cluster or supercomputer.

5. Validation process

Validation process consists of several general tests to check the ATLAS Athena computing environment and to reproduce the basic reconstruction tasks on the supercomputer cloud.

The Athena framework is an enhanced version of the Gaudi framework [13] and is widely used by the ATLAS experiment to simulate HEP events and reconstruct LHC data. Pilot jobs with different basic Athena releases were submitted and successfully finished on the NRC KI portal. Up to 100 000 events demonstrated 100% agreement. Figure 5 shows integral completed analysis jobs at the NRC-KI site during January – August 2015 on GRID Tier-1 and KI supercomputer.

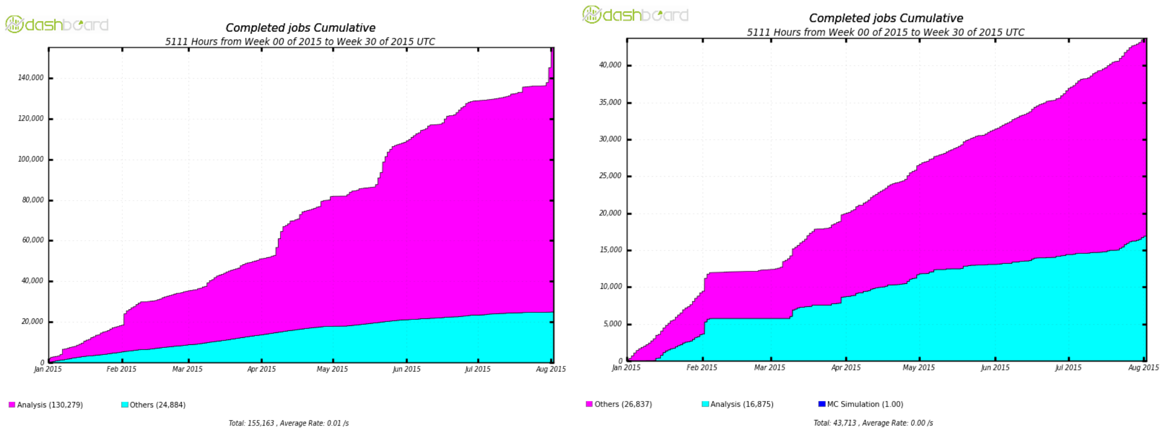
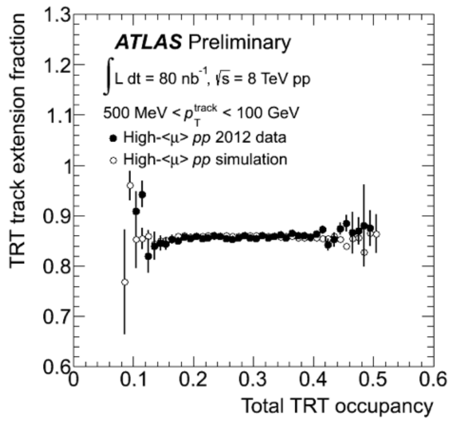


Figure 5. Completed jobs at the NRC-KI site (January – August 2015). GRID Tier-1 (left); Supercomputer (right)

Time tests used 500 reconstructed Monte-Carlo events in the ATLAS detector including detailed TRT reconstruction and showed comparable results for CPU time between CERN portal (ANALY_CERN_SLC6 site) and NRC-KI portal (ANALY_RRC-KI-T1 and ANALY_RRC-KI-HPC sites).

Physical test and the most challenged part of this study demonstrated 100% agreement in output physical data (*.root format) from CERN and KI sites for the complex TRT quantities which could be achieved only if many of simple kinematic distributions such as particle eta, pt and etc have total agreement. As an example of such complex quantities TRT extension fraction was chosen. The extension fraction is defined as the fraction of all tracks found with Si-detectors, which have more than 19 TRT hits. One of the important questions to be answered is how the TRT extension fraction depends on TRT occupancy Figure 6 presents extension fraction as a function of TRT occupancy and compares data and simulation for proton proton events. No dependence on the TRT occupancy is observed and the simulation describes the data well. This important result was obtained both on the CERN [11] and KI sites with 100% agreement.

Figure 6. TRT track extension fraction as a function of total TRT occupancy for proton-proton events. Data (solid circles) and simulation (empty circles) [11]



6. Conclusion

2000s were the decade of the GRID and during the first years of LHC data (LHC Run I) the distributed computing has managed to process and to analyze ATLAS data rapidly and to deliver physics results. The ATLAS distributed computing model allows us to incorporate opportunistic resources such as supercomputers centers and to use them efficiently now and for High-Luminosity LHC Run(s) in the future.

Supercomputers offered important and necessary opportunities to the ATLAS. We showed that we can use them efficiently for the TRT SW analysis: GRID facilities are using to generate huge sets of Monte Carlo samples, to perform complicated and resource-intensive calculations, to run the data analyses in order to obtain important physics results and other purposes. Physical tasks on HPC have been submitted using the same PanDA portal and it was transparent for physicists. Results were transferred to the ATLAS GRID site. Output data from KI HPC demonstrate total agreement in physics with identical tasks on the CERN site.

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