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Fast Simulation of Electromagnetic Showers in the ATLAS calorimeter: Frozen Showers

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Abstract. One of the most time consuming process simulating *pp* interactions in the ATLAS detector at LHC is the simulation of electromagnetic showers in the calorimeter. In order to speed up the event simulation several parametrisation methods are available in ATLAS. In this paper we present a short description of a frozen shower technique, together with some recent benchmarks and comparison with full simulation.

1. Introduction

An expected high rate of proton-proton collisions in ATLAS detector at LHC [1] requires large samples of simulated events (Monte Carlo) to study various physics processes. A detailed simulation of particle reactions ("full simulation") in the ATLAS detector is based on GEANT4 [2] and is very accurate. However, due to complexity of the detector, high particle multiplicity and GEANT4 itself, the average CPU time spend to simulate typical QCD event in *pp* collision is 20 or more minutes for modern computers.

During detector simulation the largest time is spend in the calorimeters (up to 70%) most of which is required for electromagnetic particles in the electromagnetic (EM) part of the calorimeters. This is the motivation for fast simulation approaches which reduce the simulation time without affecting the accuracy.

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Several of fast simulation methods available within the ATLAS simulation framework (standard Athena based simulation program) are discussed here with the focus on the novel frozen shower library (FS) technique. The results obtained with FS are presented here as well.

2. Electromagnetic ATLAS calorimeters

There are three main liquid-argon (LAr) EM sampling calorimeters in the ATLAS detector which cover pseudorapidity range $|\eta| < 1.475$ (barrel), $1.375 < |\eta| < 3.2$ (two end-cap components) and $|\eta| < 4.9$ (forward calorimeters FCAL), see Figure 1. Both barrel and end-cap calorimeters have accordion shaped electrodes and absorber plates over the whole coverage thus providing the full ϕ symmetry. The accordion waves vary with radius and η in both calorimeters which is important for optimisation of the performance.

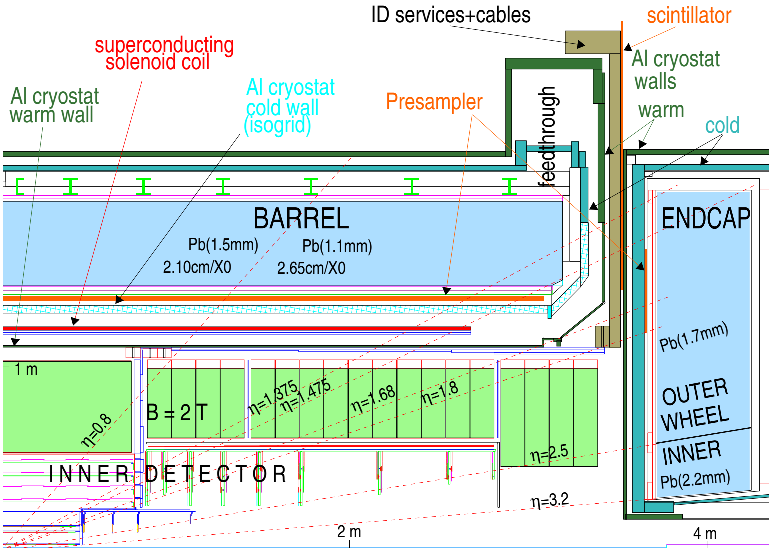

Figure 1. Layout of ATLAS EM calorimeters (FCAL is not shown).

The forward calorimeter (Figure 2) has a different layout which is motivated by the fact that the FCAL is located at high η and is exposed to a high flux of particles, thus is optimised for the best performance in high rate environment. The active material is LAr in gaps between a hexagonal array of copper tubes and rods. More information about the EM calorimeters can be found elsewhere, e.g. in [3].

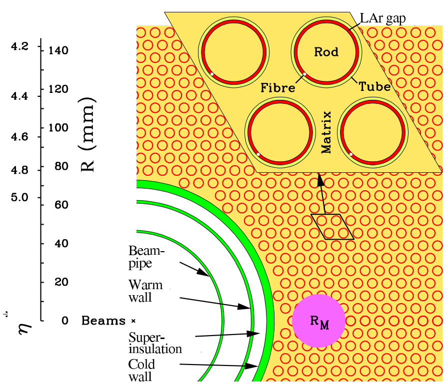

Figure 2. Schematic few of forward calorimeter module illustrating the arrangement of copper tubes and rods with LAr gaps in between.

3. Fast shower simulation techniques for ATLAS calorimeter

There are three basic approaches for the fast shower simulation in different energy ranges: High energy approach which uses parametrisation method, low energy (below 1 GeV) approach for which frozen showers are used and very low energy particle "spot" (or "killing") method.
The basic idea of parametrisation is that two, longitudinal and radial, energy distributions are sufficient to describe the spatial energy distribution of EM showers in the calorimeter. This method performs best for $e^{\pm}$ in high energy region, i.e. at energies of 10 GeV and above where calorimeter is sufficiently uniform and shower is well described by parametrised functions. The full description of the parametrisation method can be found in [4] while in [5] and [6] more details about the application of this method are given. The lower energy - frozen shower - method is an alternative approach where showers are terminated by substituting the initial low energy EM particle by the shower from the library. This method is described in the following section.
The "spot" approach is applicable only for very low energy particles where single particles ($e^{\pm}$) below 10 MeV are substituted by a single spot ("hit") with the same as the particle energy.

3.1. Frozen Showers

The frozen shower approach is well described by its name. Prior to the simulation of physics events, showers of electromagnetic particles below a certain energy cut-off (typically 1 GeV) are frozen and stored in a library for use at simulation time. Then, during simulation, when electromagnetic particles fall below that energy cut-off, the particle is stopped and a frozen shower from the library is substituted. The main steps of shower library creation are discussed in the following paragraphs.

Compression

For the library creation the incident particle of fixed energy and position (in η and ϕ) is started from the calorimeter surface. The energy of the incident particle in the calorimeter is deposited in "spots" or hits, which are subsequently recorded. For the hits spatial coordinates, energy fraction and time information are saved. The sampling fraction, the sampling fluctuations and charge-collection effects in the calorimeter are applied to the energy deposits before they are frozen. Furthermore, in order to save disk space as well as memory consumption, hit information is compressed. The compression involves two processes, *hit merging* and *truncation*:

- if the distance between any two hits in the calorimeter is smaller then a given parameter R_{min}, then hits are merged into one deposit at the energy weighted center between them. The process is repeated until no hits with distance $< R_{min}$ are left. Typical value of R_{min} is 5 mm.
- hits whose energies are below the fraction f of the total energy sum of all hits, are truncated (f is typically 95%). The energy of the remaining hits is rescaled back to preserve the total deposited energy.

In Figure 3 the shower compression steps are illustrated.

Binning

In order to follow the most important variations in shower properties the library is binned in *energy* and *position*. The same *energy* bins for all three ATLAS EM calorimeters are used, they are placed at: 1, 2, 5, 10, 20, 50, 100, 200, 500, 1000 MeV. Figure 4 shows distribution of the collected energy for each generated energy bin.
The *position* bins however are different for different calorimeters. η binning is chosen for the barrel and end-cap calorimeters since they properties, and thus the shower properties, vary strongly with η. The bins are optimised to closely follow the effective sampling variations in calorimeters. Since the variation of the response to EM particles with ϕ (due to the accordion structure of

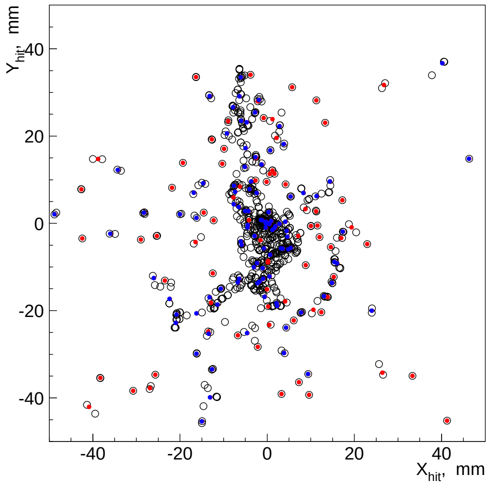

Figure 3. The transverse view of the energy deposits (hits) from a 0.5 GeV energy electron shower. The open points are original hits, red points are hits after the merging, blue points are left after the merging and truncation.

the calorimeter) is smaller than the the lateral shower size, during the creation of the shower libraries we average over ϕ position. As an example, the variation of the sampling fraction in end-cap calorimeter (caused by η dependent high voltage corrections introduced to compensate changing detector geometry) and the corresponding η binning are shown in Figure 5.

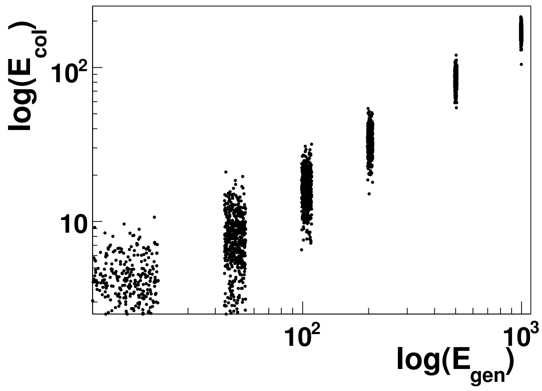

Figure 4. The correlation of the energy collected in the sensitive calorimeter detector (E_{col}) with the generated energy (E_{gen}) as recorded in the frozen shower library.

As previously mentioned, the forward calorimeter differs from other detectors by its design: contrary to barrel and end-cap, FCAL has very small active material layers (LAr gaps within copper tubes and rods). Because of this, the shower shapes in the forward calorimeter have almost no η dependence but strongly depend on the position inside the detector, i.e. the distance to the active material. Therefore the position binning for FCAL is chosen as the distance of the particle impact position from the center of the closest rod.
With a typical 1000 events in each position-energy bin, the size of the frozen shower library is about 50 MBytes for one calorimeter.

Usage of FS library
During the simulation each particle is checked for its type, energy and containment in the calorimeter. When all conditions are fulfilled (for the FS method it is: Particle is $e^{\pm}$ or γ, it is in a valid energy range and fully contained in the calorimeter), a shower from the library of corresponding energy and position bin is taken. For the particle at pseudorapidity η, the shower bin is chosen randomly from two closest pseudorapidity bins (η_1 and η_2) with a probability to take η_1 bin given as $(\eta_2 - \eta/\eta_2 - \eta_1)$. For FCAL the distance from the rod center is checked.

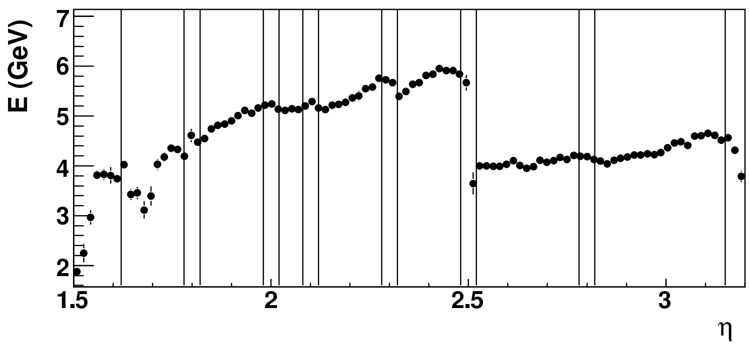

Figure 5. The energy deposited by 64 GeV electrons in the end-cap calorimeter. The library bins in η are shown as vertical lines.

The energy bin is chosen from the two adjacent energy bins (the random energy distribution follows a logarithmic distribution). Once the shower is chosen from the library, the shower hits are transformed into the ATLAS coordinate system and the total deposited energy is rescaled to the energy of the substituted particle.

3.2. Results

In this section the comparison of full and fast (FS) simulations for 64 GeV electrons simulated in various pseudorapidity regions is presented at both, simulation (before digitisation and reconstruction) and reconstruction level.

The performance of FS at simulation level is shown in Figure 6 and 7: In Figure 6 the energy response from the full simulation as a function of η (covering range from the central to forward detector region) is compared to the energy response from the FS. A good agreement with the full simulation is observed in the whole η range. Small deviations at the cracks and calorimeter edges ($\eta = 0,\ 1.4,\ 2.5,\ 3.2$) are due to incomplete shower containment where the description of showers becomes more complicated.

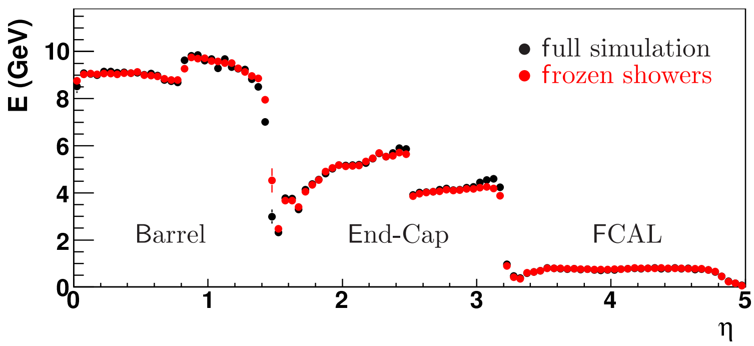

Figure 6. The comparison of energy in sampling fraction from full simulation and FS as a function of η.

In Figure 7 the CPU time in arbitrary units for full simulation and FS is shown as a function of η. As can be seen from the picture, the improvement in speed for the 64 GeV electron simulation using frozen showers can reach factor of ten and more compared to the full simulation[1].

Comparison of full and fast simulation for the shower shapes at reconstruction level for 64 GeV electrons with $\eta = 1.0$ are shown in Figure 8. Here the shower width in 3 strips of first EM barrel compartment and the lateral shower width in the second barrel compartment calculated in the window of 3x5 cells are presented. As can be seen from these examples, a good agreement between full simulation and FS at the reconstruction level is achieved.

[1] The factor of ten improvement in simulation of EM particles in the calorimeter corresponds to about a factor of two for the full simulation of a typical QCD event in ATLAS detector.

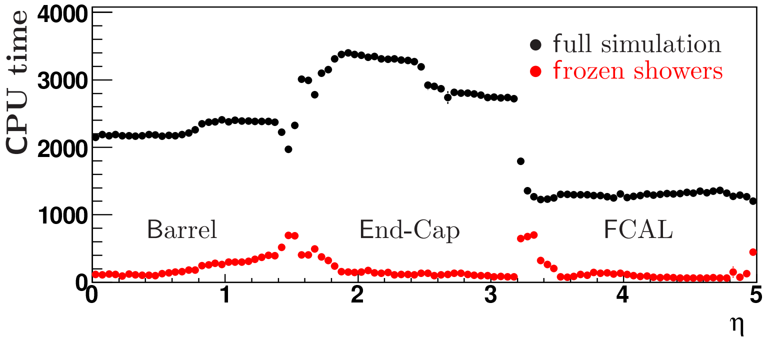

Figure 7. The comparison of simulation time from full simulation and FS as a function of η.

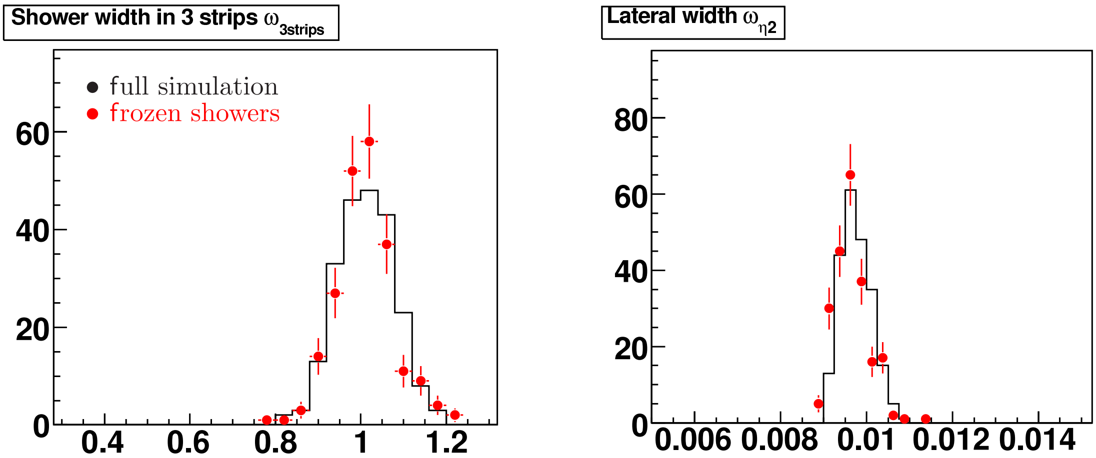

Figure 8. Shower width calculated in 3 strips in the first compartment of barrel EM calorimeter (left) and lateral shower width in the second compartment (right) for the full and fast (FS) simulation. Distributions are shown for 64 GeV and $\eta = 1.0$ electrons.

4. Conclusions

A fast simulation approach including such techniques as shower parametrisation and frozen showers has been implemented and is available for use in the ATLAS simulation framework. A short description of these methods was presented here. A significant gain in speed is achieved using the fast simulation with a good agreement of energy distributions and shower shapes over the large pseudorapidity range at both, simulation and reconstruction, level.

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