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To cite this article: A Zaborowska 2017 J. Phys.: Conf. Ser. 898 042053

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Abstract.
Software for the next generation of experiments at the Future Circular Collider (FCC), should by design efficiently exploit the available computing resources and therefore support of parallel execution is a particular requirement. The simulation package of the FCC Common Software Framework (FCCSW) makes use of the Gaudi parallel data processing framework and external packages commonly used in HEP simulation, including the Geant4 simulation toolkit and the DD4HEP geometry toolkit. Using Geant4 for full simulation implies taking into account all physics processes for transporting the particles through detector material and this is highly CPU-intensive. At the early stage of detector design and for some physics studies such accuracy is not needed, making a fast parametrised simulation better suited. Geant4 provides the tools to define a parametrisation, where the overall response of the detector is simulated in a parametric way. Many experiments create their own frameworks for these fast simulation studies. The implementation for the FCC allows an interplay between the two types of simulation within Geant4. Based on the type of the particle or a region within the detector, either full or fast simulation may be performed, running the time-consuming detailed simulation only for the regions and particles of interest.

1. Introduction
The Future Circular Collider (FCC) study has been launched to design the next generation of accelerators, hosted by the European Organisation for Nuclear Research (CERN). Three configurations of the collider are considered: lepton (FCC-ee), hadron (FCC-hh) and hadron–lepton (FCC-he). The hadron collider defines the tunnel infrastructure, with the circumference of about 100 km for the proton–proton collisions at the centre-of-mass energy of 100 TeV. The study is currently in the early stage, with the conceptual design report to be delivered in 2018.

The demands on the computer resources and their efficient exploitation by experiment software increase with every upgrade of the Large Hadron Collider. The comparison of the LHC and FCC accelerators parameters [1] shows how vital it is for the software designed for the coming experiments to rise to the even bigger challenges of future needs. Detector design studies, which have already started, require the simulation package as the first component in the FCC Common Software Framework (FCCSW).

FCCSW is based on the Gaudi software framework [2] which is used by several High Energy Physics experiments including ATLAS [3] and LHCb [4] at the Large Hadron Collider. The simulation package of FCCSW makes use of the Gaudi parallel data processing framework and...
external packages commonly used in HEP simulation, such as the Geant4 simulation toolkit [5] and the DD4hep geometry toolkit [6]. FCCSW also incorporates the Delphes framework [7] for fast simulation studies of a multipurpose detector. This allows the performance of the phenomenological studies in an idealised geometry model, simulating the overall response of the detector.

1.1. Geant4
Geant4 is a toolkit to simulate the passage of particles through matter, applied in many fields from high energy and accelerator to medical physics. It is the most common framework for full simulation studies in HEP and it is integrated into the FCC software framework. More details on the full simulation can be found in Sec. 2. Taking advantage of the tools that Geant4 provides for the implementation of the parametrisation process, it is possible to run the fast simulation for selected regions and particles, while the rest of the event is simulated in detail. Further description can be found in Sec. 3.

1.2. DD4hep
DD4hep is a detector description toolkit for High Energy Physics experiments [6]. It allows the creation of the geometry description from a single source that can be coherently used at all the event processing stages. This includes e.g. the simulation, as the automatic conversion to Geant4 geometry is supported, or the reconstruction. The configuration of the detector (e.g. detector and sub-detector dimensions, number of modules) can be easily altered from an XML file.

2. Full simulation
The aim of the full simulation is to mimic the behaviour of particles produced in the collision when they traverse the detector material. The input to the simulation is a set of particles, models of the physics processes the particles may encounter and the geometry description. The latter includes also the information which parts of the detector are sensitive to the particle passage, meaning a signal is produced when the particle-matter interaction takes place within the sensitive volume.

The simulation is performed step-by-step, taking into account all defined processes, creating secondary particles and simulating their passage as well, as depicted in figure 1. Whenever a particle traverses a sensitive material, the deposited energy is saved to be passed to the digitisation and reconstruction algorithms.

3. Fast simulation
A full simulation is very detailed and CPU time consuming. In the early stage of the detector design and often for data analysis, accuracy of the full simulation may not be needed. Hence, the idea of fast simulation was introduced, where reduction of the details results in the gain of speed.

Fast simulation is used widely in HEP experiments. The interplay between fast and full simulation can extend the possible applications. For instance, the Integrated Simulation Framework [8] developed for ATLAS allows running fast and full simulation within the same event. However, only the full simulation is performed with Geant4 and mixing of the simulation types is done at the level of the experiment framework.

3.1. General concept
There are different methods to speed up the simulation. For instance, a simplified geometry model can be used, where e.g. only detectors significant for the particular analysis are used.
Figure 1. Schema of the detailed (full) simulation. A particle is tracked step-by-step and the energy deposits are registered in the sensitive detectors.

Another possibility is not to simulate the particle passage through matter step–by–step, but instead to parametrisate the overall response of the (sub-) detector. The result of such a simulation can be the signal like the one obtained with the full simulation, e.g. the energy deposits in the calorimeter, described further in Sec. 3.4. The simplest (and fastest) parametrisation simulation replaces three time–consuming stages: simulation, digitisation and reconstruction, creating immediately e.g. tracks in the tracking detector, as described further in Sec. 3.3. Figure 2 presents an example for a particle’s passage through the detector in the fast simulation.

3.2. Fast simulation in Geant4

The input to every fast simulation are the detector–specific resolutions. The general simulation frameworks, such as Geant4, can provide the means to facilitate the parametrisation. The FCCSW fast simulation package is based on those utilities, so that fast simulation could be entirely defined within Geant4 and be used simultaneously with the full simulation.

Geant4 defines the processes, describing how particle interacts with matter. Alongside physics processes it defines the parametrisation process. It can be triggered for particles of a given type that entered a specific region and fulfilled all requirements (e.g. the energy is lower than the threshold value). Those specific requirements and also what happens to a particle that fulfills them should be defined in the parametrisation model. The model is also responsible for the transportation of the particle within the parametrised volume.

Definition of the fast simulation models is left by Geant4 to the user, with the exception of the basic implementation of GFlash library [9], described further in Sec. 3.4.

3.3. Tracking detectors

The fast simulation models for the tracking detectors in FCCSW adopt the simplest parametric approach replacing all of simulation, digitisation, and reconstruction. The parametrisation accounts for the physics effects that the particle encounters in the tracker, the detector
performance, and the reconstruction procedure. Parametrisation of muons should compensate
together with the tracker detector and the muon system.

The parametric simulation in the tracker produces tracks that can be treated as any
other reconstructed tracks, in particular, they may be used as an input to the particle flow
algorithms [10].

Once the charged particle enters the parametrised tracker it is transported directly to the
exit of the tracker, taking into account the magnetic field. The propagator, responsible for this
transportation in the magnetic field, may be identical to the one used in the full simulation, as
they are both used within the same, Geant4, framework. Furthermore, the charged particle’s
space and momentum coordinates are smeared with the distribution described by a user defined
model. The current models implemented in FCCSW smear the momentum with a Gaussian
distribution whose standard deviation describes the detector resolutions.

The resolutions may originate from our knowledge of existing HEP detectors (momentum
dependent formula) as well as from external tools, for instance those used in the tracker
performance studies. One of such tools is tkLayout [11], a tracker layout simulation toolkit
developed and used for CMS Phase 2 Upgrade studies [12]. It calculates the resolutions of the
given detector description (pseudorapidity and momentum dependent) that can be read by the
fast simulation model in FCCSW.

A more sophisticated approach of obtaining the resolutions involves a semi–automatic
procedure that simulates in detail a sample of single–particle events, reconstructs them and feeds
so-obtained resolutions to the fast simulation. Such resolutions are specific for a given detector,
hence they may be used for parametrisation with a better accuracy. Implementation of this
approach is still in progress, awaiting the track reconstruction procedure to be incorporated into
the framework.

3.4. Calorimeters

The most time–consuming part of the simulation of a typical HEP detector (ATLAS– or CMS–
like) is the electromagnetic shower development in the calorimeters, especially in the forward
regions. ATLAS reported it to be about 70% of the total simulation time for a typical physics
event [13]. That shows how crucial it is to accelerate the simulation in the calorimeters. It may
be achieved either by parametrising the shower profiles or by reusing the pre-simulated showers.

3.4.1. GFlash

GFlash is a model that parametrises the longitudinal and radial profiles of the
electromagnetic shower in the calorimeter. It has been introduced by the H1 experiment [14]
and was adopted by e.g. CDF [15] and CMS [16]. The CDF collaboration describes the GFlash
simulation to be 100 times faster than the detailed Geant4 simulation and after a proper tuning
to reproduce the average electron and hadronic response in the CDF central calorimeter with
a precision of 1–2% within the energy range 0.5–40 GeV [17]. The HF GFLASH developed for
the Hadronic Forward Calorimeter of CMS is reported to be 10,000 times faster than the full
simulation while remaining in good agreement with the 7 TeV collision data [18].

The average longitudinal shower profile can be described by a gamma distribution (Eq. (1)).

$$f(t) = \left( \frac{1}{E} \frac{dE(t)}{dt} \right) = \frac{(\beta t)^{\alpha-1} \beta \exp(-\beta t)}{\Gamma(\alpha)},$$

where $t$ is the longitudinal shower depth, $\alpha$ is the shape parameter and $\beta$ is the scaling
parameter.

The average radial energy profile can be divided into the core ($r < R_M$) and tail ($r \geq R_M$)
components as described by Eq. (2).
\[ f(r) = \left\langle \frac{1}{dE(t, r)} \cdot \frac{dE(t,r)}{dr} \right\rangle = p \cdot f_{\text{Core}}(r) + (1 - p) \cdot f_{\text{Tail}}(r) 
= p \cdot \frac{2rR_{\text{Core}}^2}{(r^2 + R_{\text{Core}}^2)^2} + (1 - p) \cdot \frac{2rR_{\text{Tail}}^2}{(r^2 + R_{\text{Tail}}^2)^2}, \]

where \( R_M \) is the Molière radius, and \( r \) is the radial distance from the shower axis (in units of \( R_M \)). \( R_{\text{Core}} \) (\( R_{\text{Tail}} \)) is the median of the core (tail) part and \( p \) is a probability of the relative weight (of the core component).

This parametrisation provides instantly an equivalent to a full shower development, not spending time on the detailed simulation. What is crucial, however, for the accuracy of the shower development parametrisation is tuning of the parameters using collision data or full simulation as a reference.

A basic implementation of the GFlash model is included in the Geant4 distribution. It does not include the correction for the magnetic field as no significant influence on the shower shape was observed [19]. Preliminary tests of the GFlash performance in FCCSW are presented in Sec. 4.

3.4.2. Frozen showers
Another approach follows a similar concept as described in 3.3 for the tracking resolutions obtained from the full simulation. For the calorimeters, the full simulation is used to create a library of electromagnetic showers. This approach is used in ATLAS [13]. Those pre-simulated showers can be used in the fast simulation in place of the costly detailed simulation. The library may also be used for only a part of the shower, for instance for particles below some energy threshold. That way the ‘core’ of the electromagnetic shower (and its possible hadronic part) would be simulated in detail, while the low energetic ‘branches’ would be taken from the frozen showers library. As the library is created for certain energies and pseudorapidity ranges, a proper scaling needs to be applied, as well as the correction for the initial particle momentum direction. However, this approach depends strongly on the detector model and it will be introduced together with more mature designs of the detector models for the FCC experiments.

4. Proof of concept
First validation tests of the Geant implementation of GFlash library were performed. The original parametrisation from [9] was used. The tested detector is the electromagnetic calorimeter barrel of inner radius 2.5 m, built of lead tungstate. Figure 3 shows the longitudinal and the radial profiles of the full simulation and the GFlash default parametrisation. They are rather well described in terms of the basic properties: the mean of the longitudinal shower and the radius of the radial profile are within 5% from the full simulation. At the bottom of the figure 3 one can see the ratio of the parametrisation compared to the full simulation in Geant. The discrepancies reach up to 25% and even more for the edge of the radial profile due to its cut-off at 10 \( R_M \). Those profiles are studied in fine binning (0.5 radiation length for the longitudinal and 0.25 Molière radius for the radial profile). The granularity of the calorimeters is much coarser and it is the total energy within the calorimeter cell that is measured. For instance, the CMS electromagnetic calorimeter is built in the barrel region of the lead tungstate crystals with a square cross section of 22 × 22 mm² and 23 cm long. The dimensions correspond to 1 \( R_M \) and 26 \( X_0 \) accordingly. This indicates that at least a basic idea on the goal calorimeter granularity should be taken into account in the study of the parametrisation performance.

This study used the original parametrisation, which can be adjusted to best describe the studied detector. This will be done once the baseline detector implementations for the FCC-hh
Figure 3. The longitudinal (left) and transverse (right) profiles of the electromagnetic shower in the calorimeter for the full simulation (filled) and GFlash parametrisation (squares) (top) and the ratio of full to fast simulation (bottom). Performed for 50 GeV electrons in PbWO$_4$ cylindrical calorimeter, with inner radius equal to 2.5 m.

and FCC-ee experiment are ready. In the meantime, for the early detector design stage, the detailed simulation is necessary. Once the geometry is fixed, the fast simulation may facilitate the physics studies, especially when it is tuned to the baseline detector.

One can already draw some conclusions from that initial study about the gain in performance of the fast simulation. The simulation run-time of the fast simulation, presented in figure 4, is about 200 times smaller than the full simulation performed for the same detector. The additional gain is in the disk space, as shown in figure 5. The cut-off of the very low-energetic tails in the GFlash simulation results in more than 100 times smaller output of the simulation, where each energy deposit is saved separately.

5. Conclusions

The common software framework for the Future Circular Collider uses the Geant4 framework to support simulation studies. Geant4 is a well-known toolkit used in various fields of physics. However, in the early design studies and also for many other applications the very detailed simulation that is provided by Geant4 may not be needed, making a fast simulation
Figure 4. The speedup of the simulation run-time for the GFlash simulation (compared to the full simulation). Performed for single electron events in PbWO$_4$ cylindrical calorimeter, with inner radius equal to 2.5 m.

Figure 5. The decrease of the size of the simulation output for the GFlash simulation (compared to the full simulation). Performed for single electron events in PbWO$_4$ cylindrical calorimeter, with inner radius equal to 2.5 m.

a more advisable approach. Many experiments use their own tools to describe the particle parametrisation. The FCC study, however, focuses on the implementation of the fast simulation within Geant4, so that a large part of the code including the reconstruction procedures can be shared. In this approach the level of detail of the simulation can be selected based on various criteria, allowing a simultaneous fast and full simulation to be performed within the same event. It has been demonstrated that both the tracker fast simulation and the GFlash shower parametrisation are now ready to be optimised for the realistic detector models.

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