PROCEEDINGS OF SCIENCE

Fast Simulation of a Time-of-Flight Detector for Forward Protons at the LHC

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Forward Proton Detectors at the CERN LHC aim to study soft and hard diffractive events from high-energy proton-proton collisions. Time-of-Flight systems at the LHC are used to reduce the back-ground from multiple proton-proton collisions. In this presentation, we describe technical details of a fast Cherenkov model of photon generation and transport through quartz bar-shaped Cherenkov radiators of a ToF detector. The fast simulation uses Python programming language and Numba - high performance compiler. The calculation is about 200 times faster than a typical Geant4 simulation and provides comparable results concerning path length and time-of-arrival distributions of photons at the photon detector. Moreover, the fast simulation allows easy computation of the time resolution of the different Cherenkov bars of such a time-of-flight detector.

The Ninth Annual Conference on Large Hadron Collider Physics - LHCP2021
7-12 June 2021
Online

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[*] Speaker

PoS(LHCP2021)159

1. Example of study: ATLAS Forward Proton ToF detector

The ATLAS Forward Proton (AFP) detector [1] aims at measuring diffractive protons leaving under very small angles (order of hundreds of µrad) the ATLAS interaction point (IP). The AFP stations are placed 205 m (near) and 217 m (far) in both directions from the ATLAS IP (Fig.1).

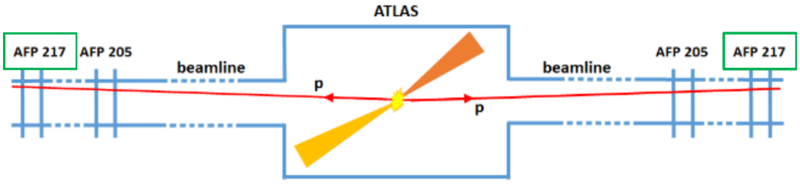

Figure 1: Position of AFP detectors in ATLAS experiment.

The far stations (noted by green boxes in Fig.1) consist of two subdetectors: Silicon Tracker (SiT) and ToF detector. The optical part of the ToF detector is composed of 16 "L-shaped" silica bars (44 LQbars); those bars are rotated by 48° with respect to the LHC beam [2]. The set of 4 bars in the horizontal row is called a train. Trains are numbered 1, 2, 3, 4; for each train, bars are denoted with letters A, B, C, D (see fig.2). Note also that train 1 has a functional improvement in design, called ”taper”, whose purpose is to straighten the photon trajectories and thus detect them in the photomultiplier (PMT) in the shortest possible time [2]. In Fig.2, we also present the coordinate system used (with orthonormal basis x, y, z).

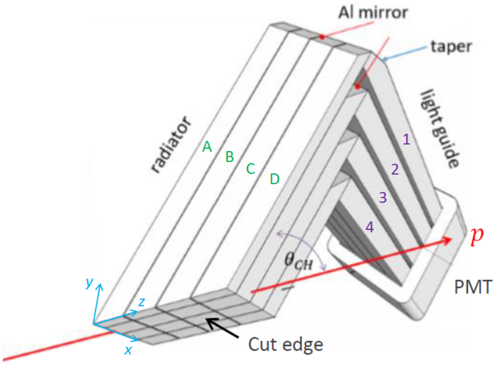

Figure 2: Optical part of the ToF detector [3].

Protons crossing the silica material (Suprasil) composing the ToF detector go faster than light, and emit Cherenkov radiation. Photons travel through the radiator, the light guide and finally to a photomultiplier (PMT). Transmission through the LQBars can be viewed in the approximation of geometrical optics, with internal reflections and losses [4].

2. Fast simulation

2.1 Fast simulation flow

We present here the different steps of the fast simulation:

Generation of proton trajectories → Generation of Cherenkov photons → Photon tracking through the ToF detector (radiator and light guide) → Photons reach the photomultiplier (PMT)

2.2 Attenuation effects

In whichever the case, the absolute majority of photons bounce on the sides of the radiator and the sides of the light guide. Depending on the incident angle, a photon can be reflected or not. The following attenuation effects are implemented in the fast simulation [3, 5]:

- reflectivity on the Al. mirror (90%);
- aach time the light ray hits a side (bound) and satisfies the conditions of total reflection, we use 99% as the value of probability of reflection;
- attenuation in the material (silica), which is function of the wavelength of the photon. The probability of absorption is given by: $p_{\text{abs}} = 1 - e^{\mu_{\text{abs}} L}$ with $\mu_{\text{abs}} = \frac{1}{L_{\text{abs}}}$ the attenuation coefficient of the material and L_{abs} the attenuation length [6, 7].

2.3 Track length and time

We denote L the length of photon track between a vertex A and the PMT ($L = L_{A \to \text{PMT}}$). The time-of-flight includes the time a proton spends when travelling from $t = 0$ to the vertex A (with length noted L_{p}), and the time-of-flight of the photon (from vertex A to the PMT):

$$t = t_{\text{p}} + t_{\gamma} = \frac{L_{\text{p}}}{c} + \frac{L}{c/n} \tag{1}$$

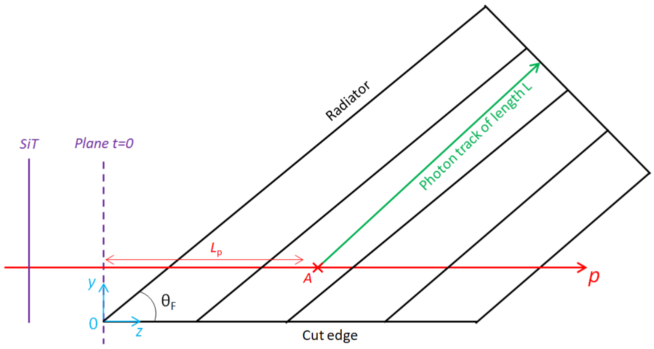

Figure 3: Illustration of time measurement from the vertical plane ($t = 0$) to the PMT.

A photon coming from a vertex in a bar can go in another bar if it's not reflected on the side between the two bars: this is the phenomenon of optical cross-talk.

3. Fast simulation vs Geant 4

3.1 Comparison of length and time distributions for the case of a full train

In order to compare the results of the fast simulation and Geant4, we performed the simulation by generating 10^5 Cherenkov photons with random positions of vertices, for a fixed trajectory of proton. We represent in Fig.4 the distributions of lengths and times of photon arrivals obtained for train 2. About 43% of initial photons reach the PMT, and the percentages of geometrical cases are 42% case 1; 19% case 2; 39% case 3.

The distributions have similar shapes, and the relative error is less than 2% (in absolute value) for 95% of photon tracks (Fig.5). The fast simulation is then in a good agreement with Geant4.

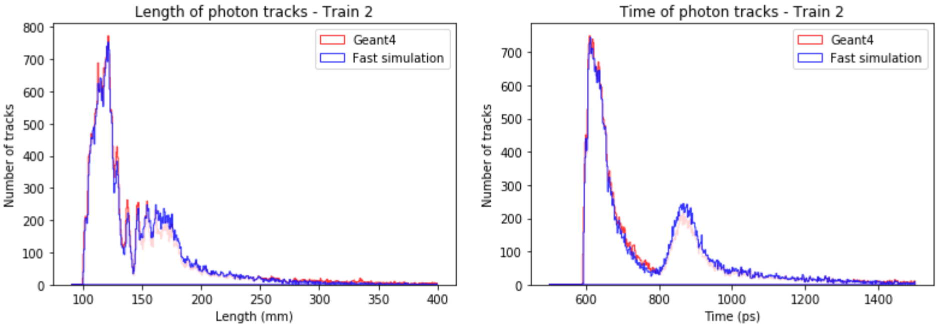

Figure 4: Histogram of photon track lengths and times - train 2.

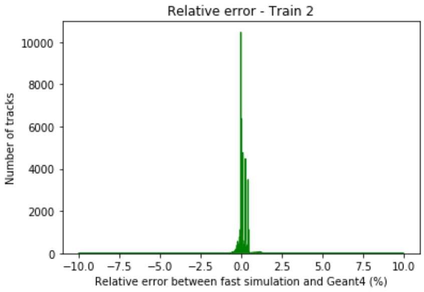

Figure 5: Relative error $(L - L_{\text{geant}})/L_{\text{geant}}$ for photon tracks.

3.2 Speed of the simulations

By generating initially $3, 3.10^6$ photons using a computer with Intel Core i7-2600K 3,4 GHz, 32GB RAM, we get the following results for the duration of the simulations:

Geant4 simulation	Geometrical method in C++	Fast simulation (Python+Numba)
11,5 minutes	20 seconds	3 seconds

The fast simulation is then about 200 times faster than Geant4 simulation.

4. Conclusion

We presented the fast modeling of the AFP Time-of-Flight detector, that uses the geometrical method. The distributions of lengths obtained by the fast simulation and Geant4 have the same shape, with relative difference $< 2\%$. An advantage of the fast simulation compared to Geant4 is the speed-up of a simulation; it is about 200 times faster, and allows one to generate a higher number of proton trajectories, thus improving statistics. The code of the fast simulation, written in Python 3, is available at: `https://github.com/olivierrousselle/Fast-simulation-AFP`. Users can choose the train, the number and positions of proton trajectories they want to model, and other parameters as the material of bars.

We suggest that such a fast simulation with Python and Numba could be used to model other types of ToF detectors.

References

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