CERN Summer student report:

Fast simulation of the ATLAS Forward Proton detector

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Abstract

This article describes technical details of the Fast Cherenkov model of photons generation and transportation through the optical part of the Time of Flight Detector of the ATLAS Forward Proton detector (AFP). The results are compared to the ones obtained with Geant4, concerning the length of photon tracks and attenuation.

Presentation of the AFP detector

The AFP detector is one of four forward detectors of the ATLAS experiment at CERN. AFP's stations are placed 205 m and 217 m in both directions from the ATLAS interaction point (IP). The AFP Detector aims at observing protons that are scattered during collisions by a very small angle (diffractive processes). It consists of two subdetectors: Silicon Tracker (SiT) and Time-of-Flight (ToF) detector [1].
We want to model the photon trajectories (length of tracks) inside the ToF detector, in order to evaluate the shape of distributions.
Protons crossing the Silica material (Suprasil) composing ToF go faster than light, and then emit Cherenkov radiation.
The optical part of the ToF detector is composed of 16 "L-shaped" bars called LQbars. The set of bars in the horizontal row is called a train (fig. 1).

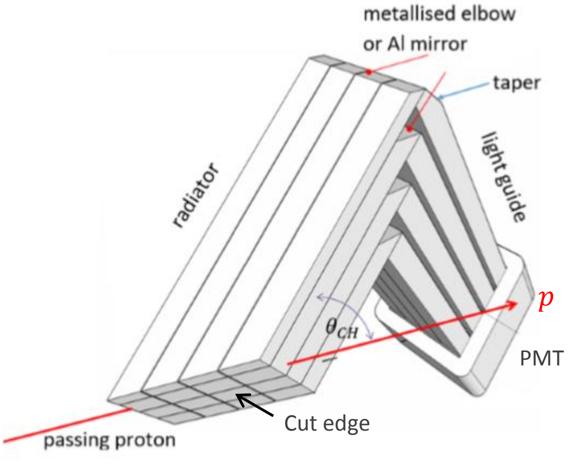

Fig. 1: Optical part of ToF

Light rays travel through the radiator (RAD), the light guide (LG) and finally to the photomultiplier (PMT). Transmission through LQBars can be viewed in the approximation of geometrical optics, with internal reflections and losses.

The trajectory of photons inside the detector has been already simulated by using Geant4.

Geant 4 simulation

Geant4 is Monte Carlo toolkit to simulate the passage and interactions of elementary particles with matter. Geant4 has a structure with runs, events, tracks and steps. In our case, a run corresponds to set of proton beams going through the detector, an event corresponds to one proton, a track corresponds to a photon emitted from a vertex of the beam, and a step corresponds to a photon trajectory from one side to another side of the detector.
Geant4 contains a module called *G4Cerenkov* which models Cherenkov process for a given material with a refraction index [2].

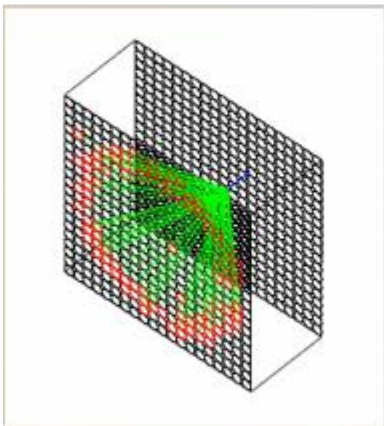

Fig. 2: Cherenkov process modelled by Geant4 [3]

G4OpticalSurface models the photon propagation. It includes the physics processes of refraction and reflection at medium boundaries, bulk absorption and Rayleigh scattering. Moreover, the reflection can be total or not (Fresnel reflection).

However, Geant4 simulation of Cherenkov photons is relatively slow, and we expect the geometrical method presented here to be faster than Geant4 [4]. Our work is in continuity with Katerina Jirakova's thesis [5].

Parameters of the study

We represent below the dimensions of the train 2 – bar A, by using different views of it (fig. 3).

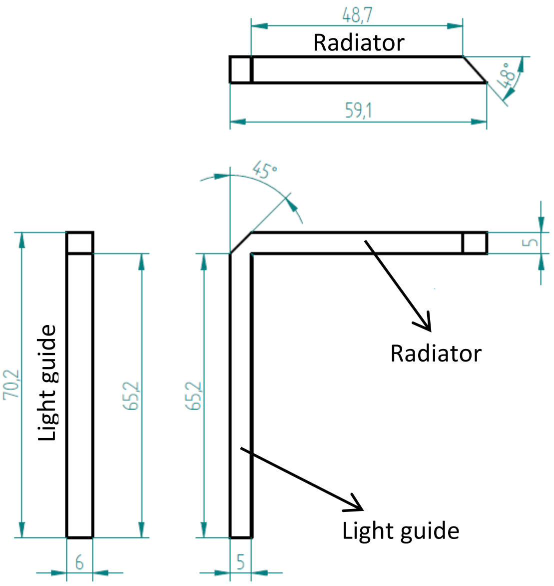

Fig. 3: Dimensions of the bar 2A (in mm)

Here, the length of the radiator is $L_{rad} \approx 65{,}2\text{ mm}$ and the length of the light guide is $L_{lg} \approx 59{,}1\text{ mm}$.

We use the following coordinate system, where the origin lies on the cut edge (fig. 4).

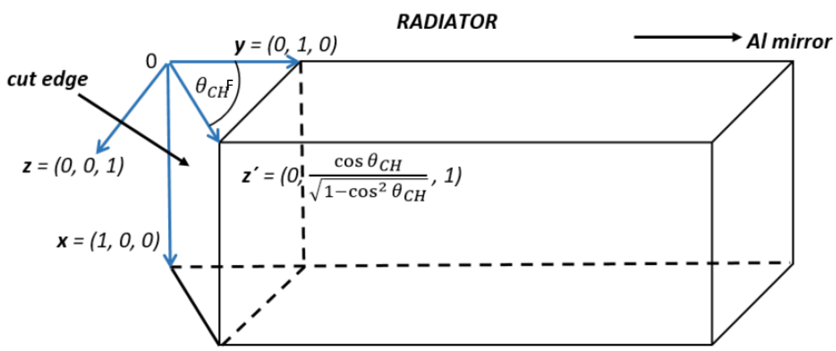

Fig. 4: Definition of the coordinate system

Proton beams and Cherenkov photons:
We simulate protons with different kinematics. Each proton has a certain angle with respect to the cut edge; in our study, we mainly will consider only proton beams parallel to the cut edge and with y-intercept of 2mm.
Each proton trajectory represents a source of Cherenkov photons. The average number of photons generated is given by the formula [2]:

$$\mu \approx 370. Z^2. \text{StepLength}. \int_{E_{min}}^{E_{max}} \left(1 - \frac{1}{n^2(E).\beta^2}\right)$$

with $Z = \frac{q}{e} = 1$ the multiplicity of proton's charge;

StepLength the length of proton beam from one side to the other side of the radiator;

$\beta = \frac{v_p}{c}$ the relativistic factor of the proton; here we keep $\beta = 1$;

E the energy of photons corresponding to wavelengths in the range $[180\text{nm} ; 650\text{nm}]$;

n the refraction index of silica.

In the proton beam, photons are emitted from different points, called vertices. Let's call $A(x_A, y_A, z_A)$ one of the vertices.

In the program, a wavelength is attributed randomly (in the range $[180\text{nm} ; 650\text{nm}]$) to each photon.

Light coming from the Cherenkov effect is emitted under a certain angle, called Cherenkov angle θ_{ch}. This angle depends on the refraction index n, and thus on the wavelength of the photon. Its value is: $\theta_{ch} = \arccos\left(\frac{1}{\beta.n}\right)$. For silica, $\theta_{ch} \approx 48°$.

Each photon is generated randomly with an angle $\varphi \in [-\pi; \pi]$, indicating the direction of the light ray inside the Cherenkov cone (fig. 5).

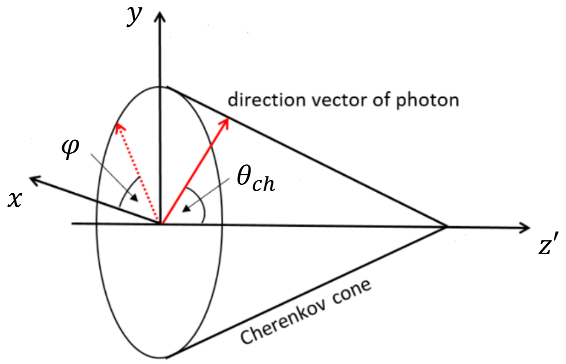

Fig. 5: Illustration of Cherenkov cone and associated angles [5]

All the parameters useful for our study are illustrated in the Appendix.

Possible cases

We distinguish 4 different geometrical cases:

- Case 0: the light ray doesn't reach the photomultiplier;
- Case 1: the light ray touch the Aluminium mirror and goes to the photomultiplier (fig. 6);
- Case 2: the light ray doesn't touch the Al mirror and goes to the photomultiplier (fig. 7);
- Case 3: the light ray goes to the cut edge and after goes to the photomultiplier.

We illustrate the cases 1 and 2 in the following figures. The real trajectory of the photon is represented in pink color.

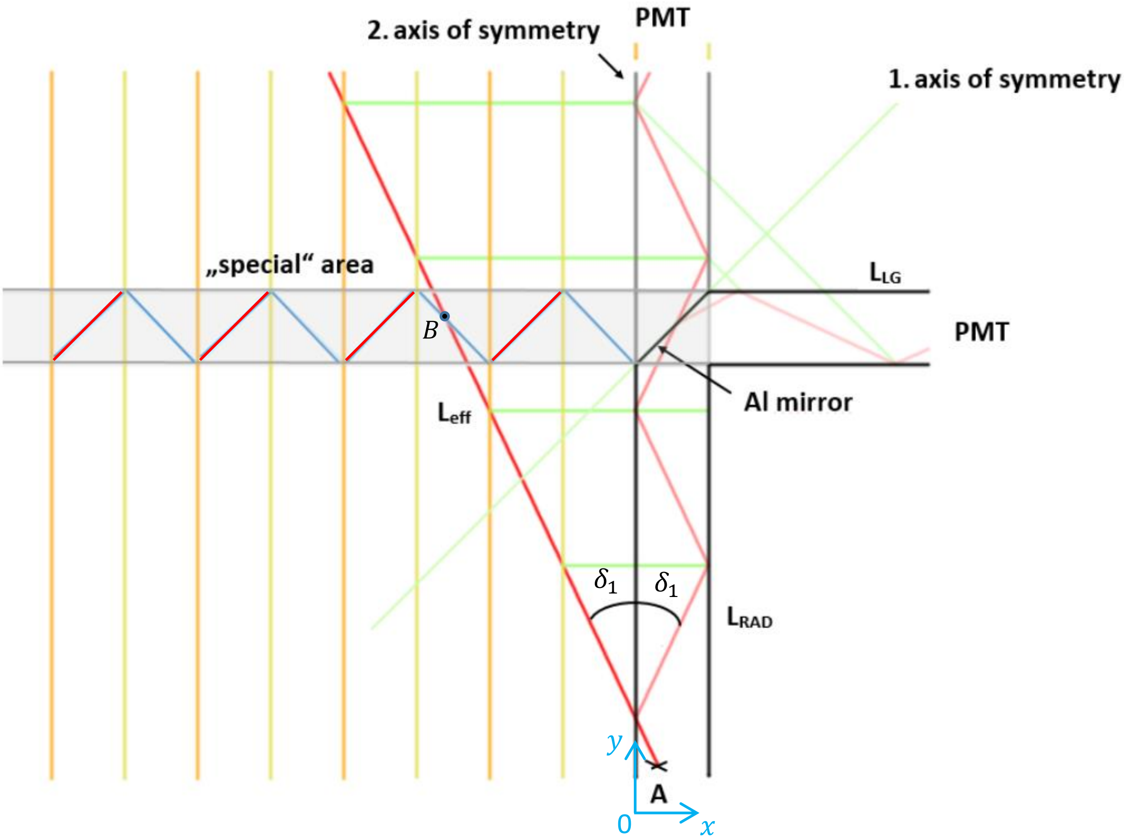

Fig. 6: scheme illustrating the case 1 [6]

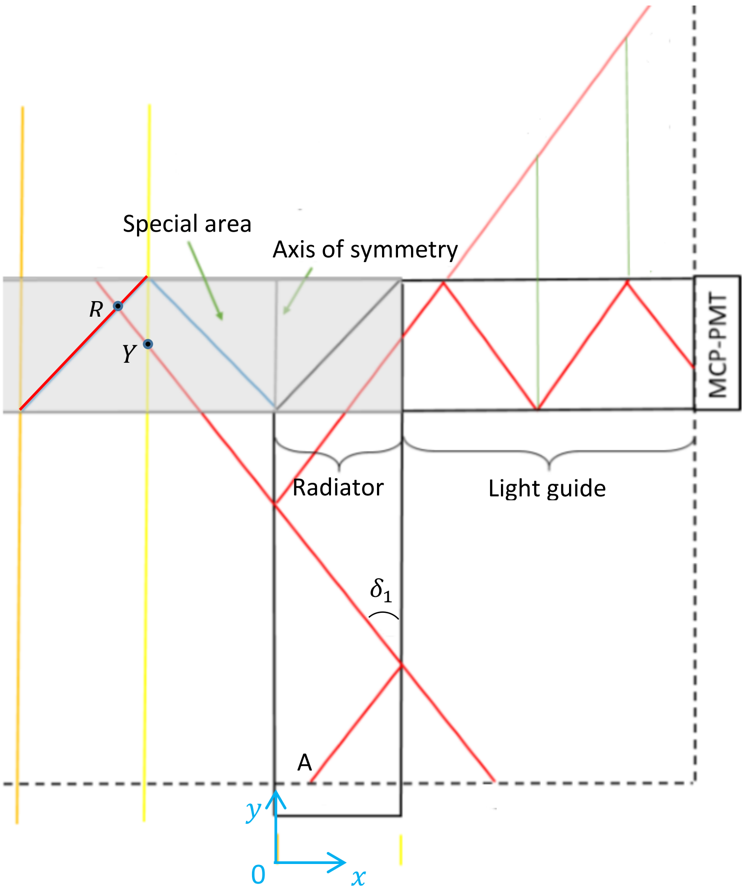

Fig. 7: scheme illustrating the case 2 [6]

We call by:

- B the crossing point between the straighten light ray (in red) and the blue diagonal (projection of the Al mirror), within the so called "special area" (grey color);
- R the crossing point between the light ray and the red diagonal (projection of the Al mirror), within the "special area";
- Y the crossing point between the light ray and the yellow vertical line, within the "special area".

To distinguish between the different cases, we use the following conditions:

1. if B exists $\rightarrow$ case 1;
2. if R exists and Y exists $\rightarrow$ case 2;
3. if R exists, Y doesn't exist and $\delta_1 < \pi/4 \rightarrow$ case 1;
4. if R exists, Y doesn't exist and $\delta_1 > \pi/4 \rightarrow$ case 0.

Calculation of the length of photon trajectory

Case 1:
By using fig. 6 and angles represented in the Appendix, the length of the light ray from point A to the PMT is given by:

$$L = \frac{L_{rad} - y_A}{\cos(\alpha_1).\cos(\delta)} + \frac{L_{lg}}{\cos(\alpha_2).\cos(\delta_3)} \tag{1}$$

Case 2:
We call Y the intersection point between the light ray and the yellow line within the special grey area (fig. 7).
Now the length between point A and PMT is given by:

$$L = \frac{y_Y - y_A}{\cos(\alpha_1).\cos(\delta)} + \frac{L_{lg}}{\cos(\alpha_2).\cos(\delta_3)} \tag{2}$$

Case 3:
It's the case where the photon hits the cut edge. We call A' the intersection point between the light ray and the cut edge.
For the calculation of the length between A and PMT, we do the same study as for case 1 / 2 by using A' as the new initial point, and we add the length between A and A':

$$L_{A \rightarrow PMT} = L_{A' \rightarrow PMT} + [AA'] \tag{3}$$

We can also calculate the time of the photon trajectory, from the vertex point to the PMT. It is given by:

$$t = \frac{L}{v} = \frac{L}{n_{silica} c} \tag{4}$$

Attenuation effects

Whatever the case, a photon ray bounces on the sides of the radiator and the ones of the light guide. Depending on the incident angle, it can be reflected or not (fig. 8).

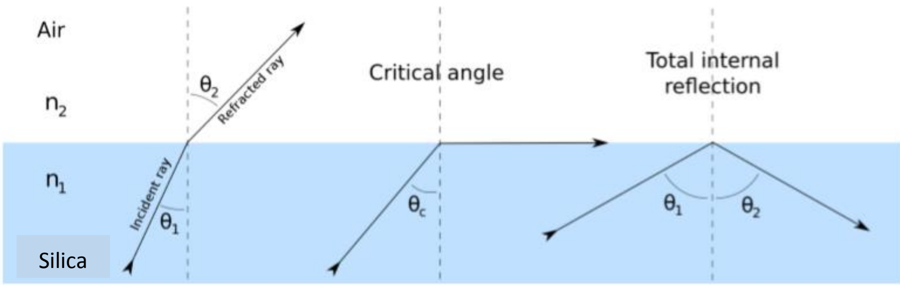

Fig. 8: Condition of total reflection

There are four different incident angles and conditions of total reflection to consider, corresponding to the different sides of the bar (see Appendix for details):

- $\theta_{r0} > \theta_c$ (on plane 0 of the radiator), with $\cos(\theta_{r0}) = \sin(\alpha_1) . \cos(\delta)$
$$\rightarrow \cos(\theta_c) > \sin(\alpha_1) . \cos(\delta) ; \quad (5)$$

- $\theta_{r1} > \theta_c$ (on plane 1 of the radiator), with $\cos(\theta_{r1}) = \sin(\delta)$
$$\rightarrow \cos(\theta_c) > \sin(\delta) ; \quad (6)$$

- $\theta_{r2} > \theta_c$ (on plane 2 of the light guide, only for case 2), with $\cos(\theta_{r2}) = \cos(\alpha_1) . \cos(\delta)$
$$\cos(\theta_c) > \cos(\alpha_1) . \cos(\delta) ; \quad (7)$$

- $\theta_{r3} > \theta_c$ (on the cut edge, only for case 3), with $\cos(\theta_{r3}) = \sin(\alpha) . \cos(\delta)$
$$\cos(\theta_c) > \sin(\alpha) . \cos(\delta). \quad (8)$$

The following attenuation effects are also implemented in fast simulation [5]:
- Reflectivity on the Al mirror (90%), relevant for the case 1;
- Each time the light ray hits a side (bound) and satisfy 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:
$$p_{abs} = 1 - e^{-\mu_{abs}(\lambda).L} \quad (9)$$
with $\mu_{abs} = \frac{1}{L_{abs}}$ the attenuation coefficient of the material and L the length of photon trajectory.
L_{abs} is the attenuation length which is a function of wavelength; its evolution is taken from [7].

If a light ray satisfies the conditions of reflection through its full path and is not absorbed, it will be detected by the photomultiplier.

Results of fast simulation

Simulation of a bar:

We simulate one bar, for example the bar 2A (longest bar in the train 2), with the following proton beam parallel to the cut edge:

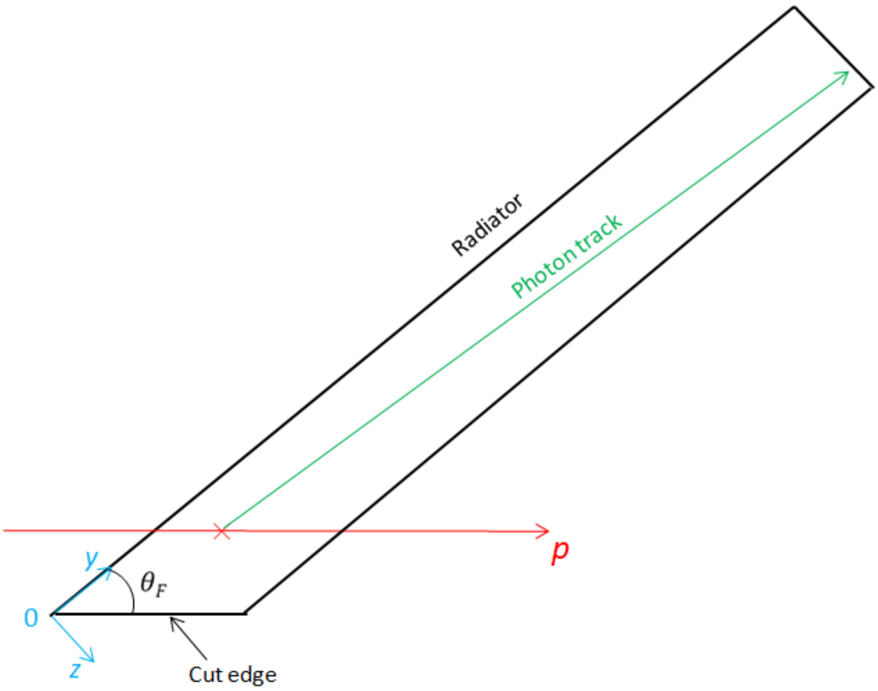

Fig. 9: illustration (in 2D) of a bar

We simulate 59 events (protons), and for each event in average 850 photons are generated. So the total number of photons generated is about 50000.

In fast simulation, about 42% of the initial photons reach the PMT; it's the same rate in Geant4 simulation.

In fast simulation, the repartition of cases among photons reaching the PMT is:

- 46% for case 1;
- 14% for case 2;
- 40% for case 3.

For each photon reaching the sensor, we calculate the length between A (vertex point) and the PMT with the formula described previously (1-2-3), and the time for such trajectory (formula 4).

We represent in the following figures the histogram of length of photon tracks, as well as the histogram of time. For each figure, we represent the distribution obtained with Fast simulation and the one obtained with Geant4.

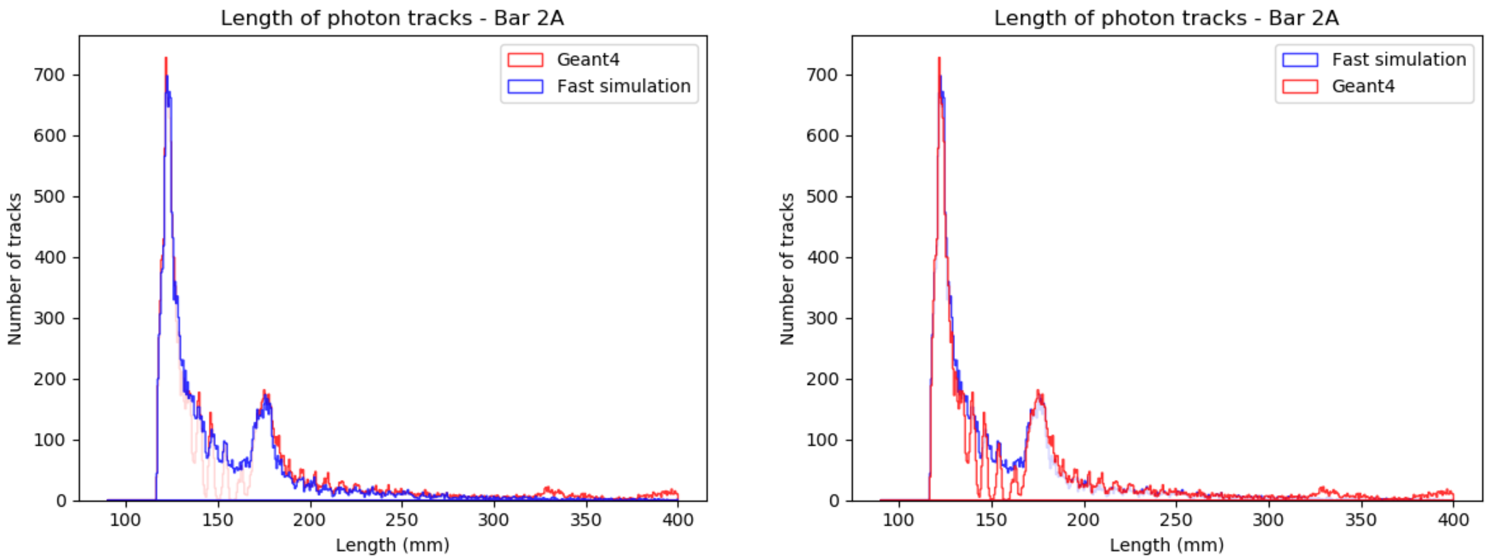

Fig. 10: histograms of **length** distributions – bar 2A

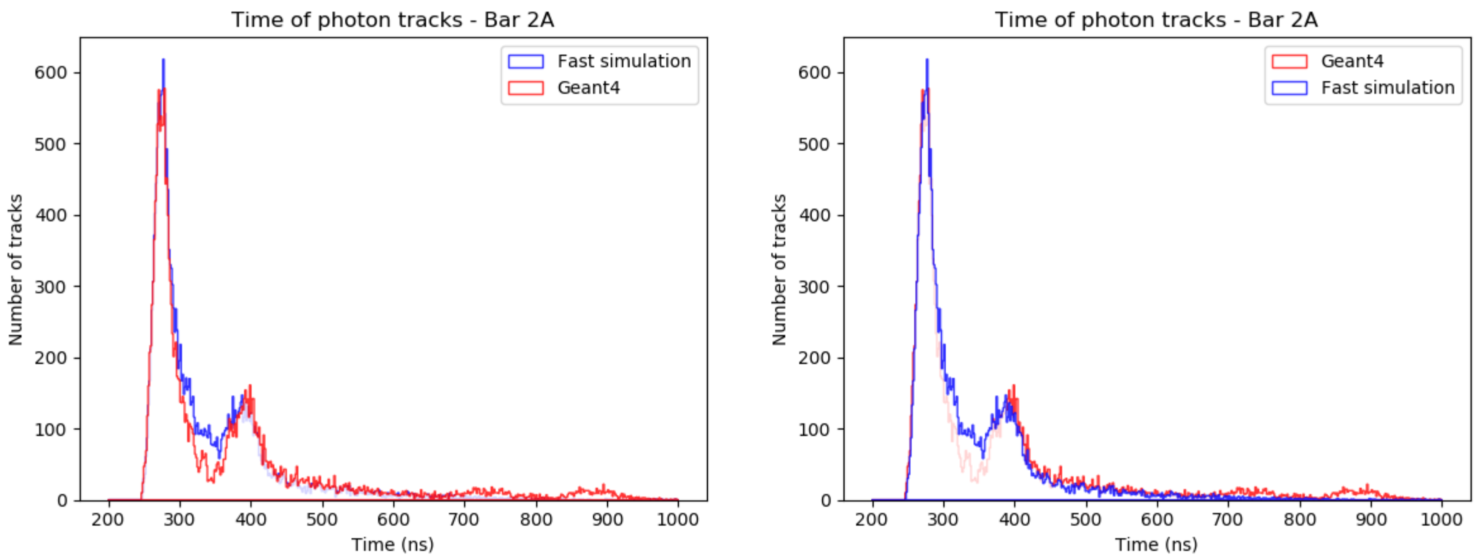

Fig. 11: histograms of **time** distributions – bar 2A

We see that the distributions have the same shape, although we can notice some differences for tracks of length around 150 mm.

For each track reaching the PMT, we extract the length obtained with Geant4 and we compare it with the length obtained by fast simulation by calculating the relative error (fig.12).

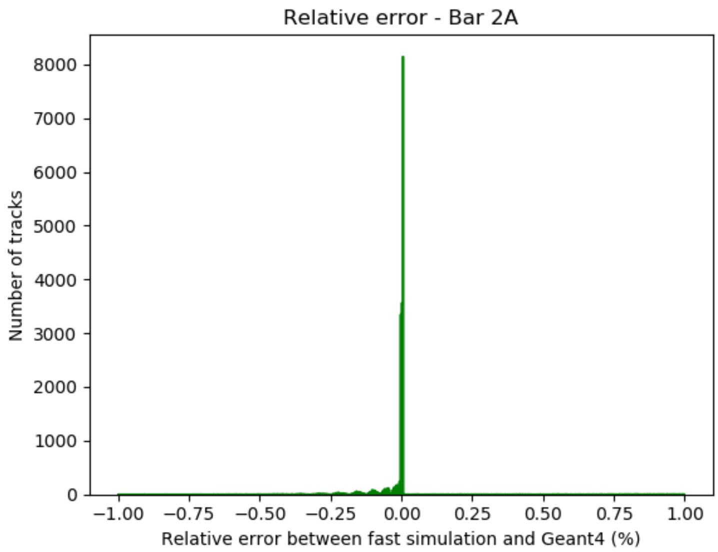

Fig. 12: histogram of relative errors between fast simulation and Geant4 – bar 2A

We see here a big peak at 0%, and the relative error is less than 0,25% (in absolute value).

Simulation of a train:

We can also model a train, composed of 4 bars.
An important effect to consider is the cut edge effect: a light ray can go to another bar, provided that there is no reflection on the side of the bar.

We did the simulation of train 2. In fig. 13, we illustrate the proton trajectory used (in red) and examples of cut edge effect (in green).

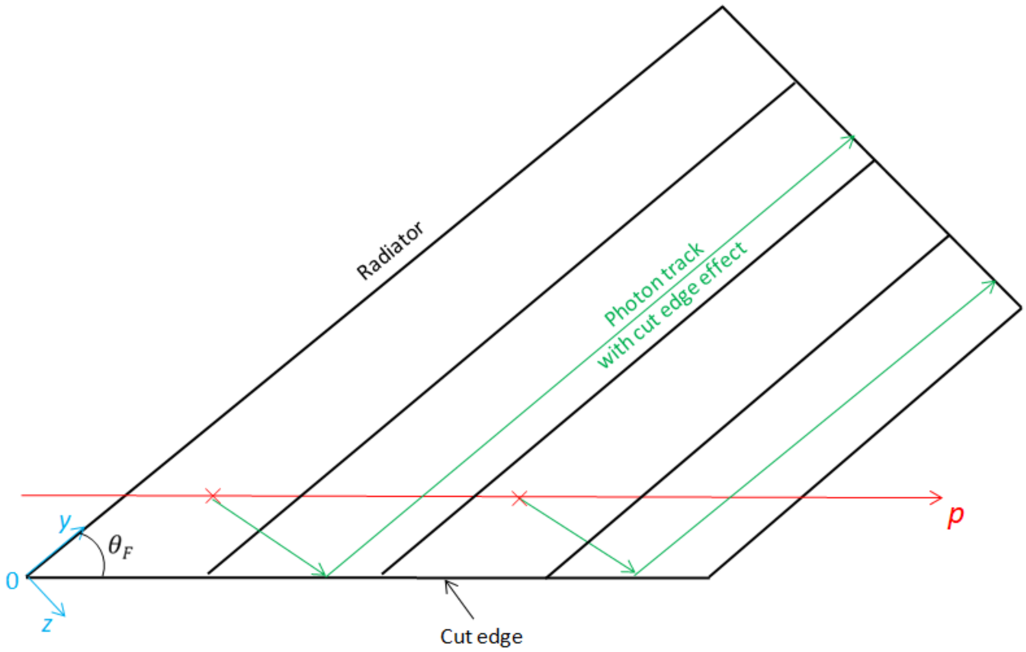

Fig. 13: illustration (2D) of a train

We simulate 30 events (proton beams), and for each event about 3300 (4 x 850) photons are generated. So the total number of photons generated is about 100000. In fast simulation, about 43% of initial photons reach the PMT; in Geant4, about 45% of them reach the PMT.

In fast simulation, the repartition of cases among photons reaching the PMT is:

- 42% for case 1;
- 19% for case 2;
- 39% for case 3.

We show below the distributions of lengths and times, for fast simulation and Geant4.

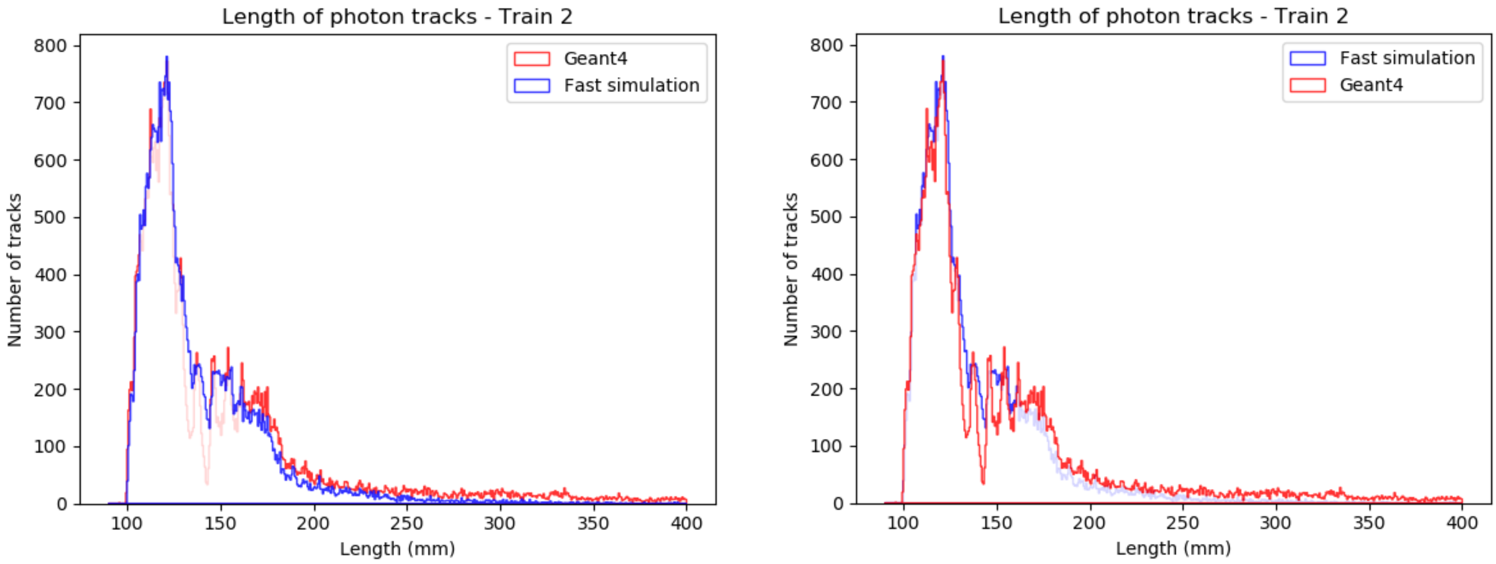

Fig. 14: histograms of **length** distributions – train 2

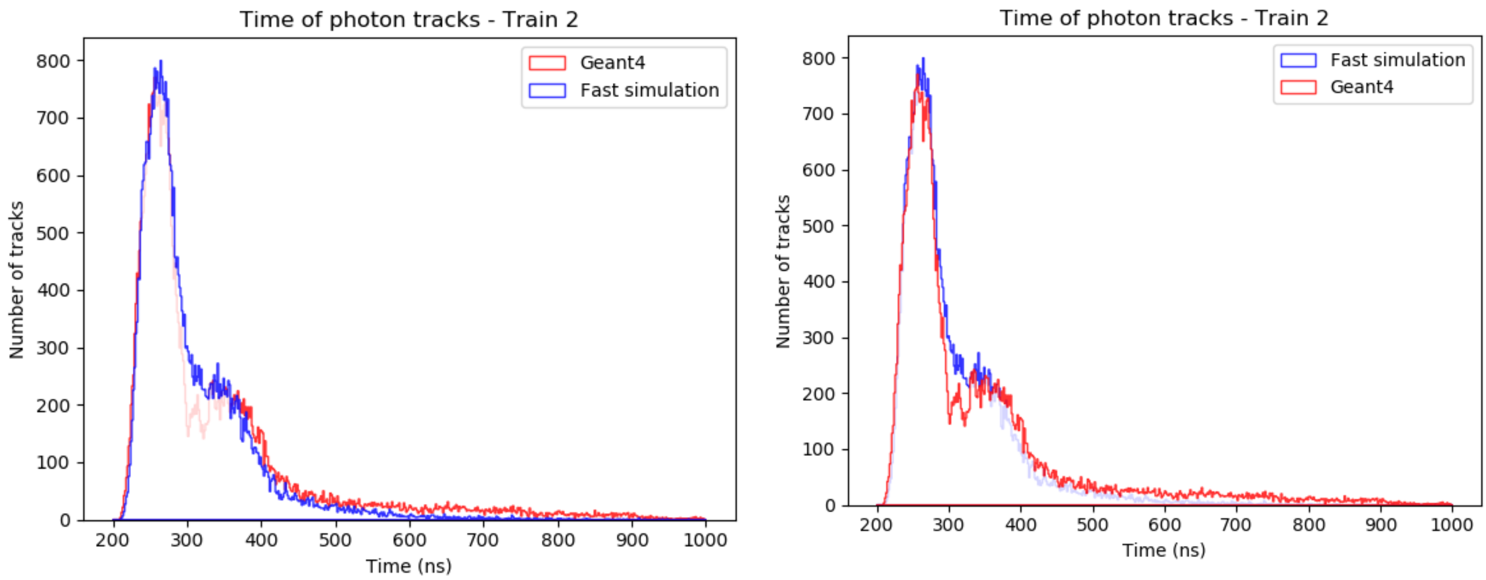

Fig. 15: histograms of **time** distributions – train 2

We see that the distributions have the same shape, although there are some differences that are non-trivial to explain (particularly around 150 mm). Moreover, the attenuation in fast simulation seems too important for high length (> 200 mm).

For each track reaching the PMT, we extract the length obtained with Geant4 and we compare it with the length obtained by fast simulation by calculating the relative error (fig. 16).

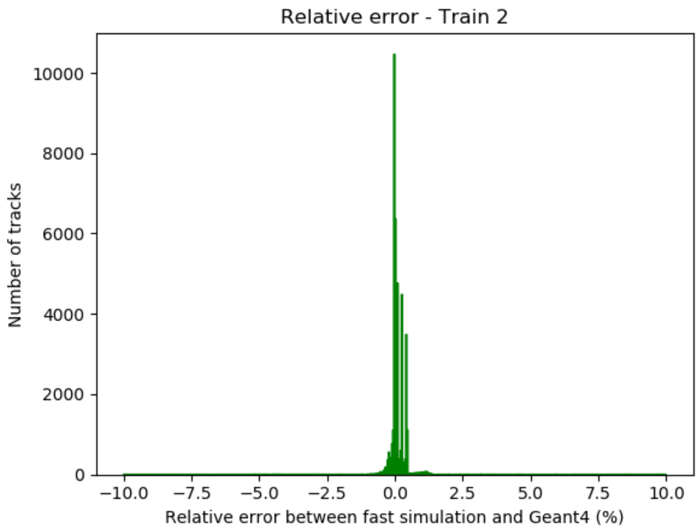

Fig. 16: histogram of relative errors between fast simulation and Geant4 – train 2

As for the bar 2A, we see here a big peak at 0%, and the relative error is less than 2% (in absolute value).
Fast simulation is then in good agreement with Geant4 for the calculation of lengths.

Conclusion

We presented here the modeling the Time-of-Flight detector, by using a geometrical method.
The distributions of lengths obtained by fast simulation and Geant4 have the same shape, and the proportion of photons reaching the PMT is also nearly the same. This confirms Geant4 simulation for those points.
An advantage of fast simulation compared to geant4 is the time of simulation: by simulating 3.300.000 photons using a computer with Intel Core i7-2600K 3,4 GHz, 32GB RAM, the Fast simulation took about 2,1 minutes whereas the Geant4 simulation took 11,5 minutes; it is then about 5 times faster.
The code of the fast simulation, written in Python 3, is available here:
https://github.com/olivierrousselle/Fast-simulation-AFP
The user can choose the bar or the train he wants to model, the number and position of proton beams generated, and the coefficients of attenuation.

Acknowledgement

I would like to thank Tom Sykora and Andrea Dell'Acqua for having supervised me during the CERN summer student program. Particularly for their passion in physics, their kindness, and for this interesting project mixing physics, computing and geometry.
I also want to thank Libor Nozka for providing Geant files for comparison and overall support with Geant.

References

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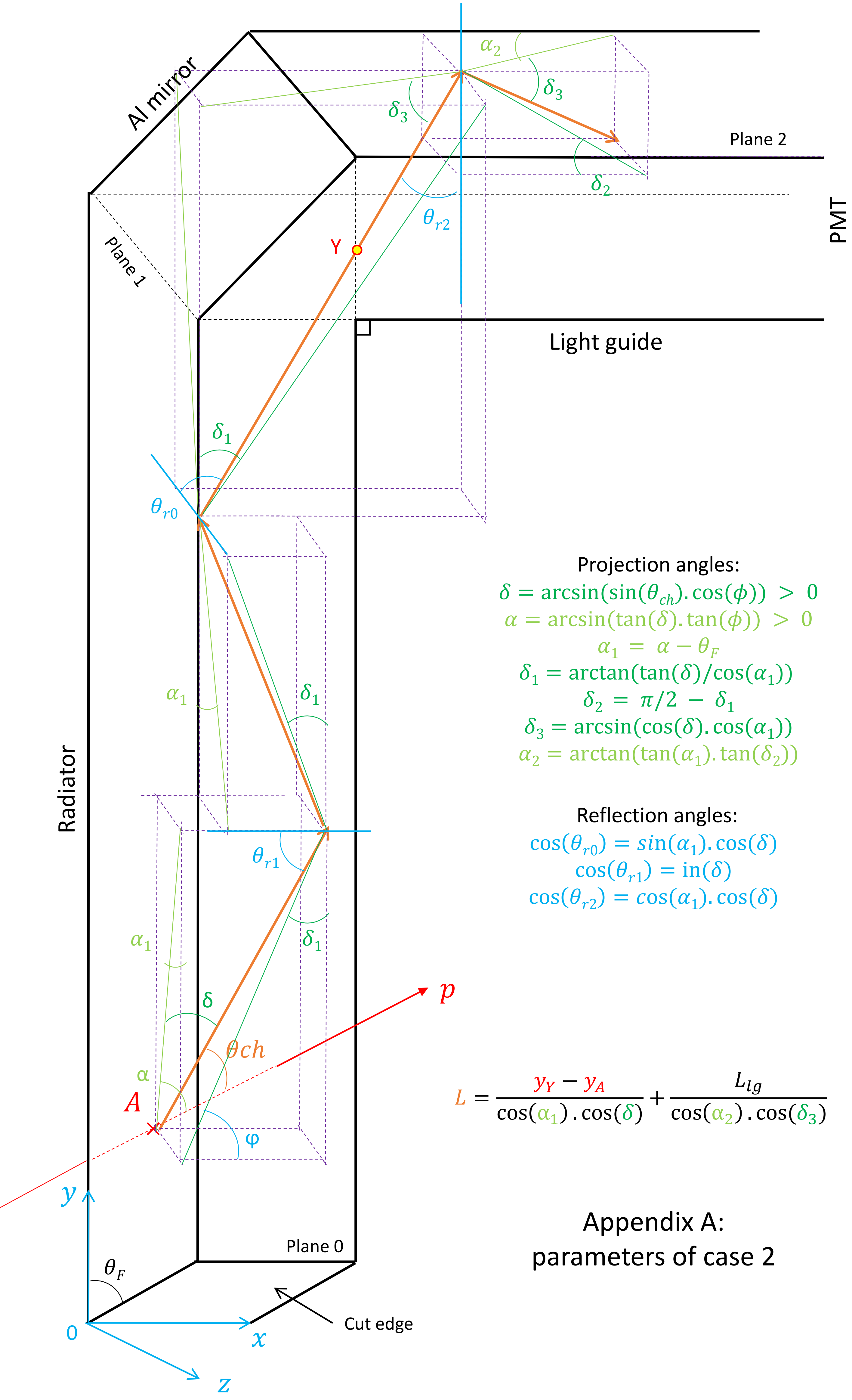
Appendix:

Illustrations of the parameters of fast simulation - ToF Detector



Projection angles:

$$\delta = \arcsin(\sin(\theta_{ch}).\cos(\phi)) > 0$$
$$\alpha = \arcsin(\tan(\delta).\tan(\phi)) > 0$$
$$\alpha_1 = \alpha - \theta_F$$
$$\delta_1 = \arctan(\tan(\delta)/\cos(\alpha_1))$$
$$\delta_2 = \pi/2 - \delta_1$$
$$\delta_3 = \arcsin(\cos(\delta).\cos(\alpha_1))$$
$$\alpha_2 = \arctan(\tan(\alpha_1).\tan(\delta_2))$$

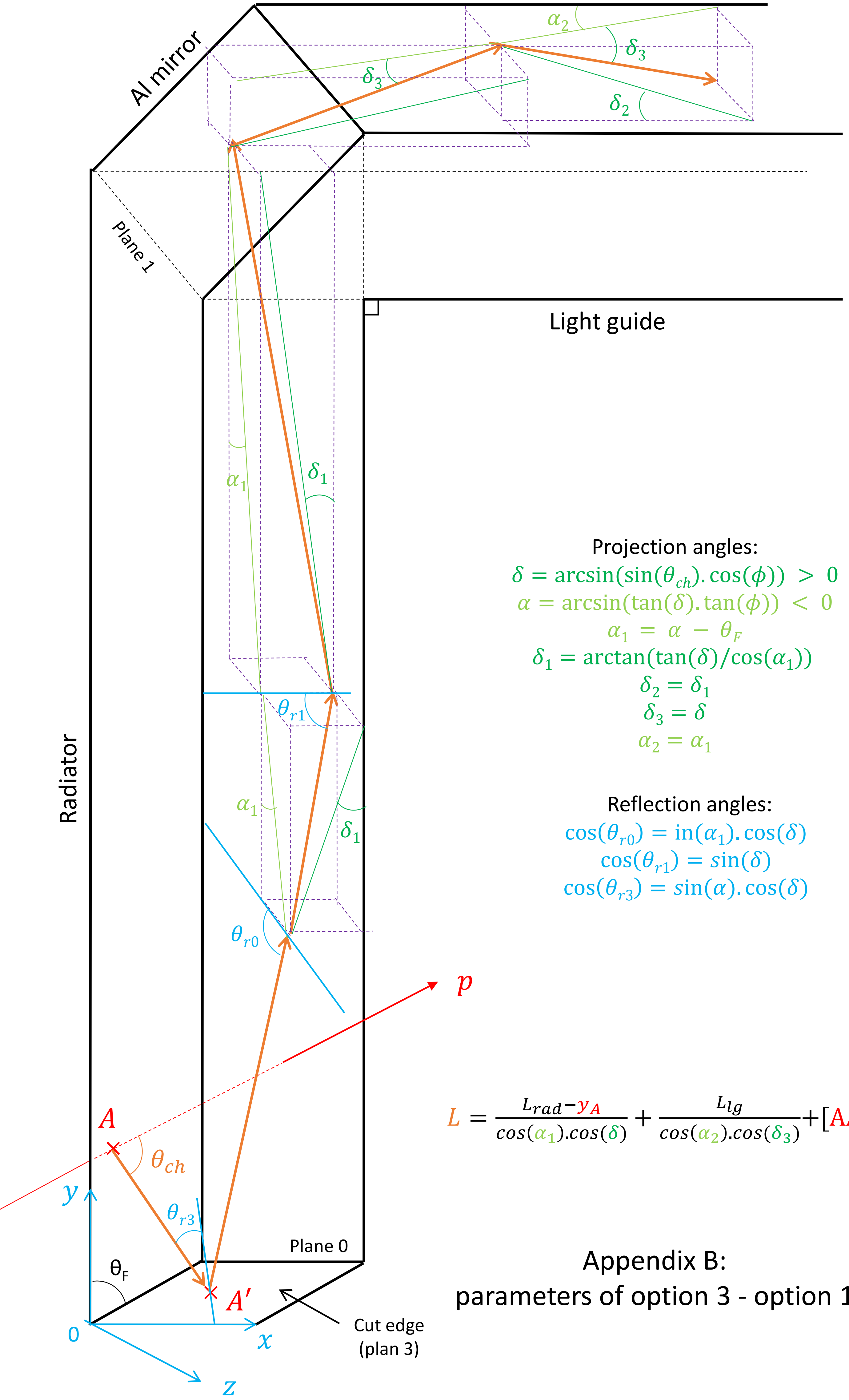
Reflection angles:

$$\cos(\theta_{r0}) = \sin(\alpha_1).\cos(\delta)$$
$$\cos(\theta_{r1}) = \mathrm{in}(\delta)$$
$$\cos(\theta_{r2}) = \cos(\alpha_1).\cos(\delta)$$

$$L = \frac{y_Y - y_A}{\cos(\alpha_1).\cos(\delta)} + \frac{L_{lg}}{\cos(\alpha_2).\cos(\delta_3)}$$

Appendix A: parameters of case 2

Appendix B: parameters of option 3 - option 1



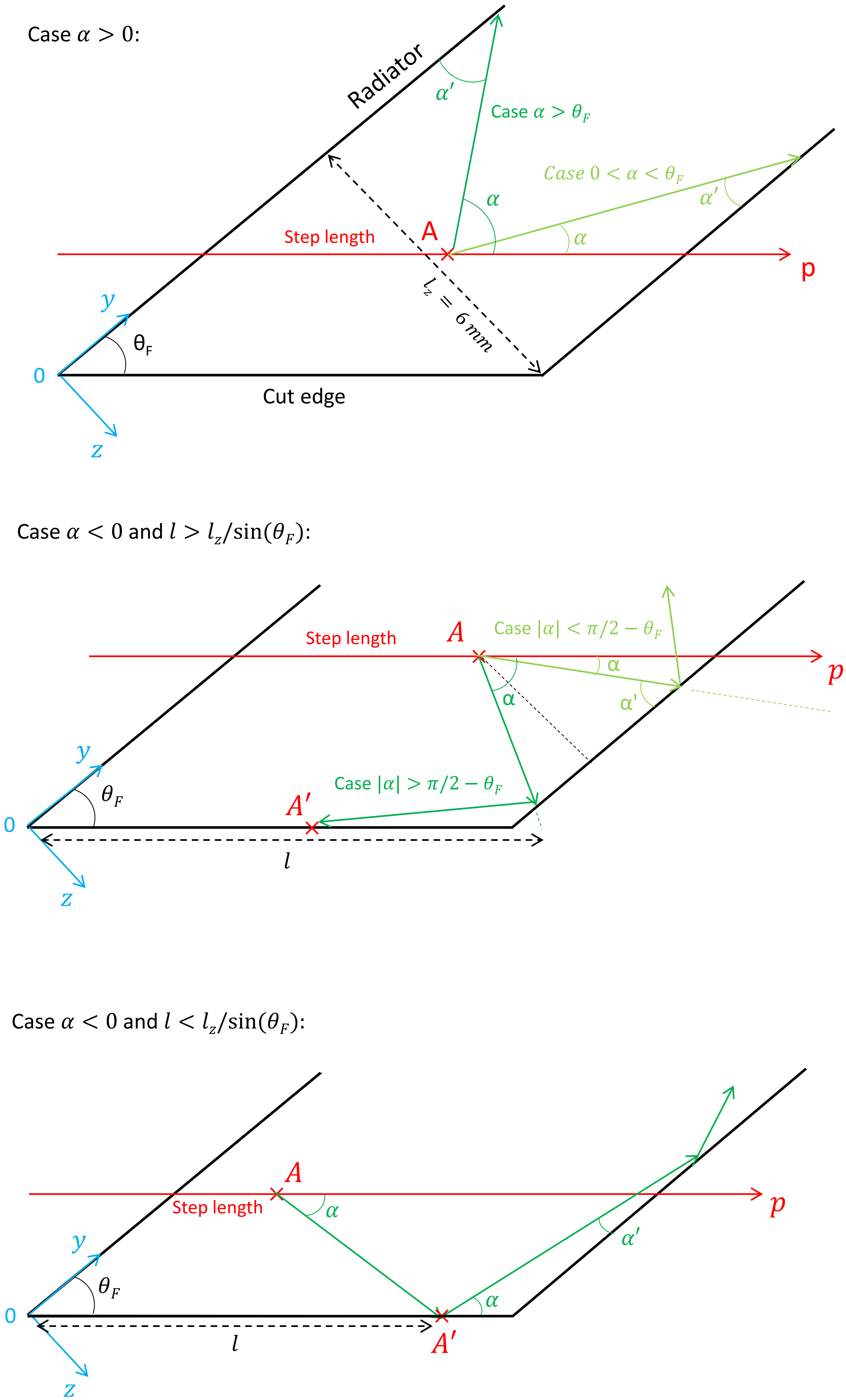
Projection angles:

$$\delta = \arcsin(\sin(\theta_{ch}).\cos(\phi)) > 0$$
$$\alpha = \arcsin(\tan(\delta).\tan(\phi)) < 0$$
$$\alpha_1 = \alpha - \theta_F$$
$$\delta_1 = \arctan(\tan(\delta)/\cos(\alpha_1))$$
$$\delta_2 = \delta_1$$
$$\delta_3 = \delta$$
$$\alpha_2 = \alpha_1$$

Reflection angles:

$$\cos(\theta_{r0}) = \mathrm{in}(\alpha_1).\cos(\delta)$$
$$\cos(\theta_{r1}) = \sin(\delta)$$
$$\cos(\theta_{r3}) = \sin(\alpha).\cos(\delta)$$

$$L = \frac{L_{rad} - y_A}{cos(\alpha_1).cos(\delta)} + \frac{L_{lg}}{cos(\alpha_2).cos(\delta_3)} + [AA']$$



Appendix C:
different cases in the plane y-z