National Centre for Nuclear Research Świerk

ŚWIERK COMPUTING CENTRE

Simulation of J-PET detector response with the GATE package

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1. Introduction – GATE package

GATE - Geant4 Application for Tomographic Emission
Website: http://www.opengatecollaboration.org/

Features of GATE:
- physics implemented using Geant4 framework
- possibility of taking into account many physical processes in the same moment using just few lines of code
- simplicity of script language which reduces time of preparing the simulation
- facilities in defining geometry (e.g. repeaters)
- possibility of usage of advances phantoms, like XCAT v.2 (phantom 4D)
- simulations of phenomenons that are dependent on time (movement of detector, impact of phantom breathing, changing activity of source)
- applications in PET, SPECT, CT and RT

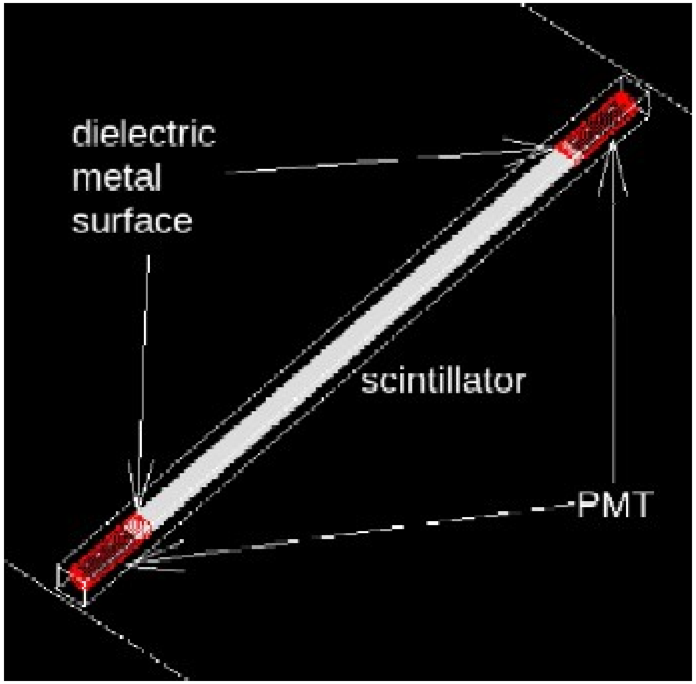
1. Introduction – common elements of all simulations

Material EJ230 $C_{10}H_{11}$:
- density: 1.023 g/cm3
- scintillation yield: 10240 1/MeV
- refractive index: 1.58
- absorption length: 110 cm

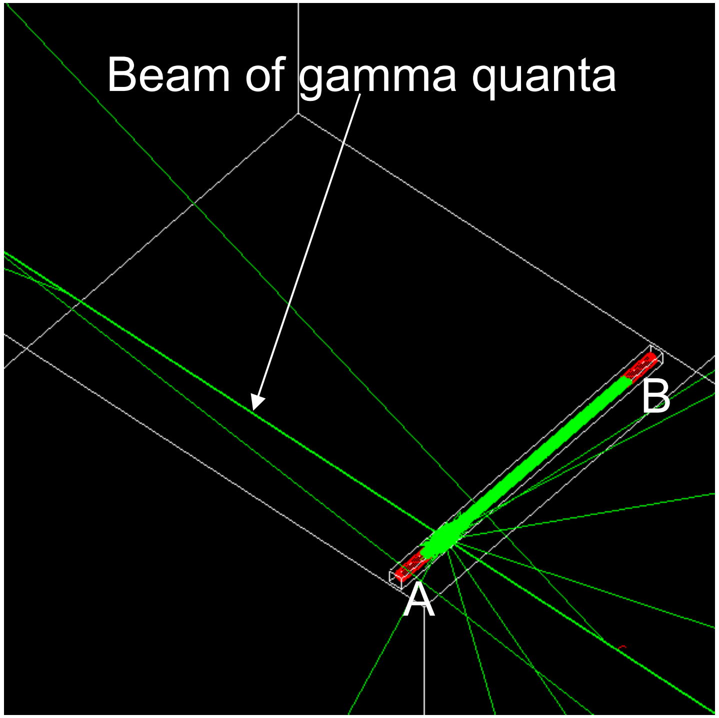
Geometry:
- size of scintillators: 19x5x500 mm
- photomultipliers defined as dielectric-metal surfaces

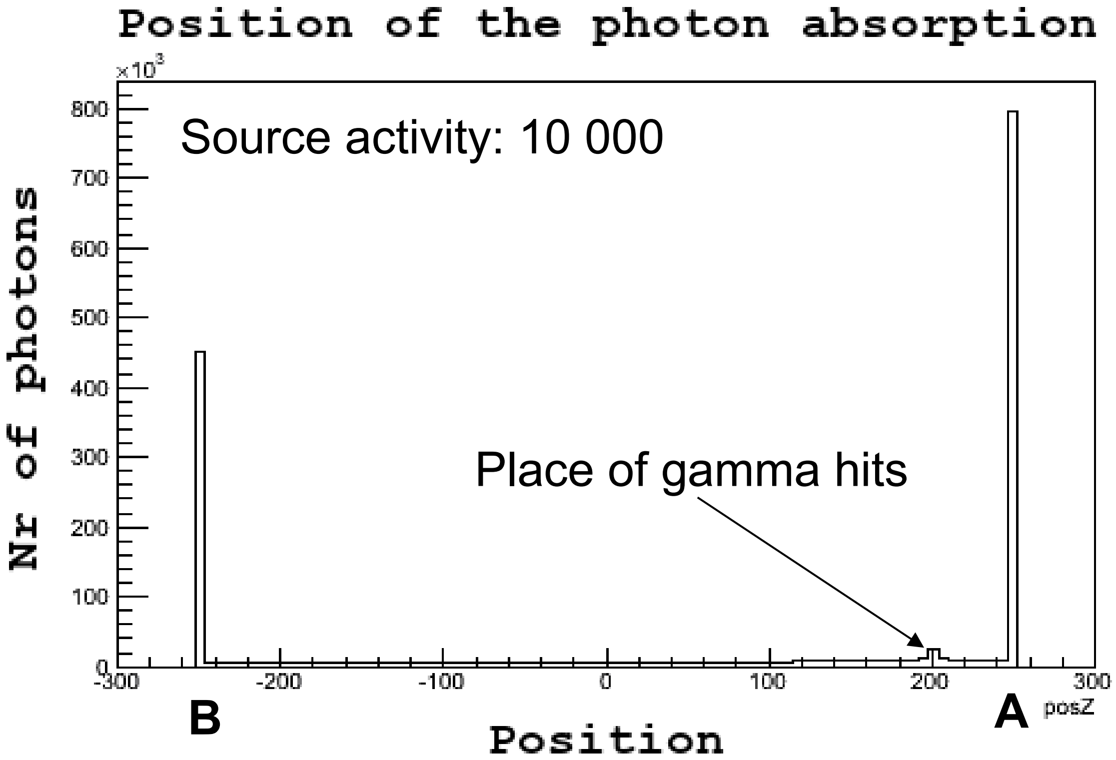
Sources:
- beam, point or rectangular region
- back-to-back gamma particles with energy 511 keV

Physics:
- photoelectric effect, Compton effect, scintillation, boundary effects, etc.



2. Single detector response to a beam source





- simulation: beam of 10.000 gamma quanta directed into the scintillator
- most of generated photons was transported to the "photomultipliers" and absorbed by the dielectric-metal surfaces (bigger nr of photons at pmt which was nearer to place of hit)

2. Single detector response to a beam source

Algorithm of calculating of the voltage signal:

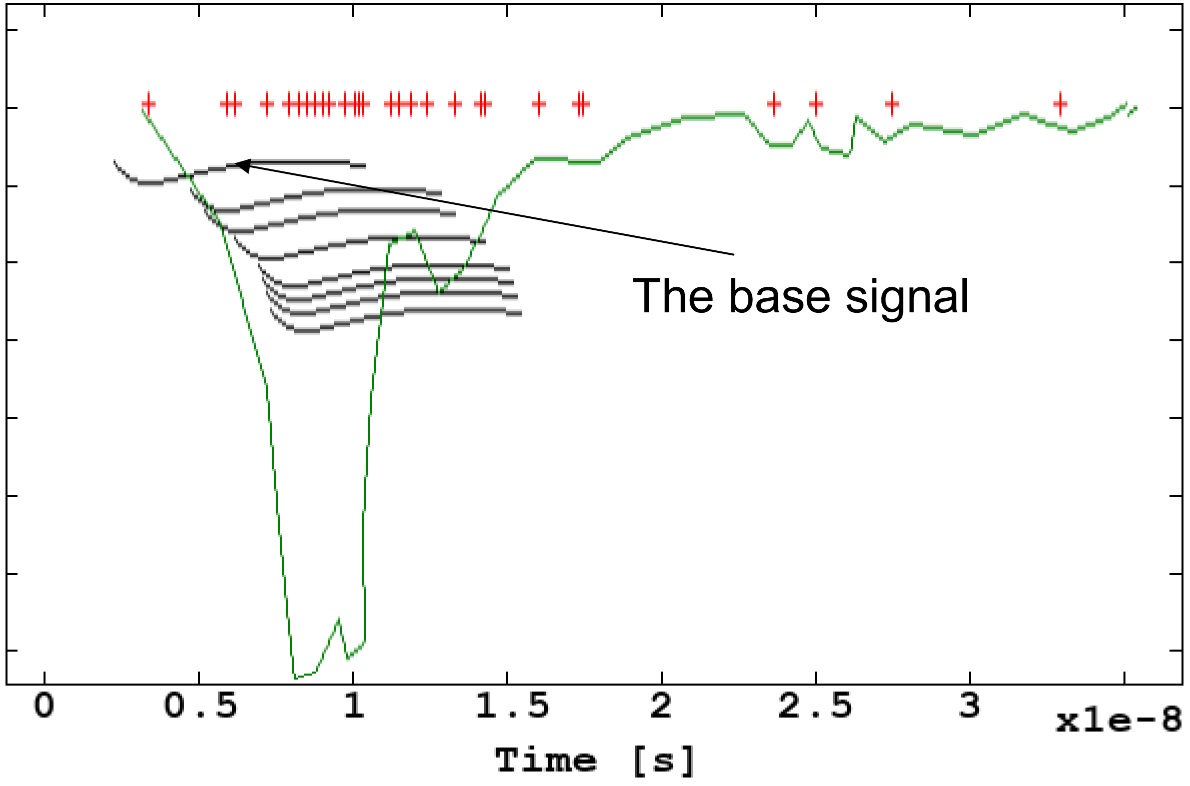
1. All photons (there is no limit for wavelength) from single event that reached the surface between scintillator and photomultiplier, are treated as photons detected by the photomultiplier.

2. Times of arrivals of photons to the surface are treated as the „shifts” of the voltage signals of single photons (data from experiment) during calculating final voltage signal.

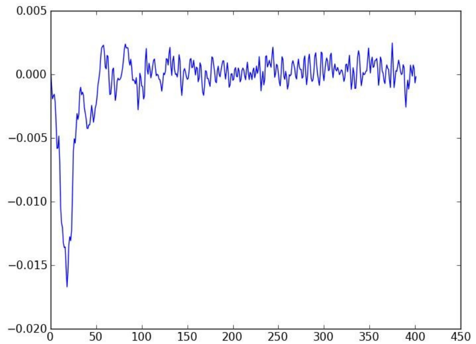
3. For each photon, voltage signal is randomized from the base of voltage signals and added to the final voltage signal with relevant time shift.

2. Single detector response to a beam source

Illustration of alg. of calculating voltage signals:



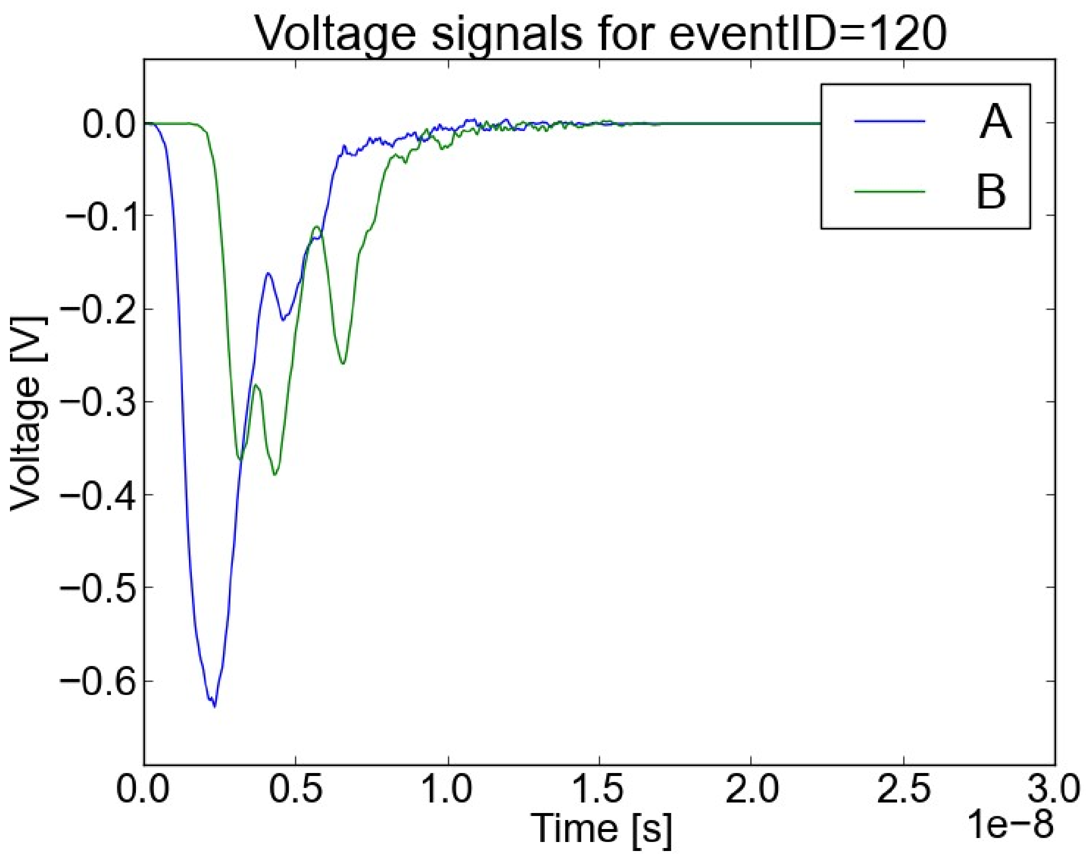
Example base signal for supply voltage of F2 pmt equal 2400V:



In further calculations, base of 15 signals for F2 photomultiplier was used (supply voltage 2400V).

2. Single detector response to a beam source

Example voltage signals, generated for one of events:



- place of first scintillation located nearer to A pmt
- duration ~5 ns
- second smaller peak in both signals, may by connected with photons reflected inside the scintillator

3. Simulations of 2-detector system

Definition:

Map of efficiency f(z,r)

z – axis of the scanner

r – radius of the scanner

1. Assumption: points of annihilation are generated uniformly at the region of the cylinder with length Z0 and radius R0

2. Cross section of the cylinder along the z axis (containing the diameter) is shared virtually into pixels with width dz and d

3.

$$f(r,z) = N_{acc}(r,z) / N_{gen}(r,z),$$

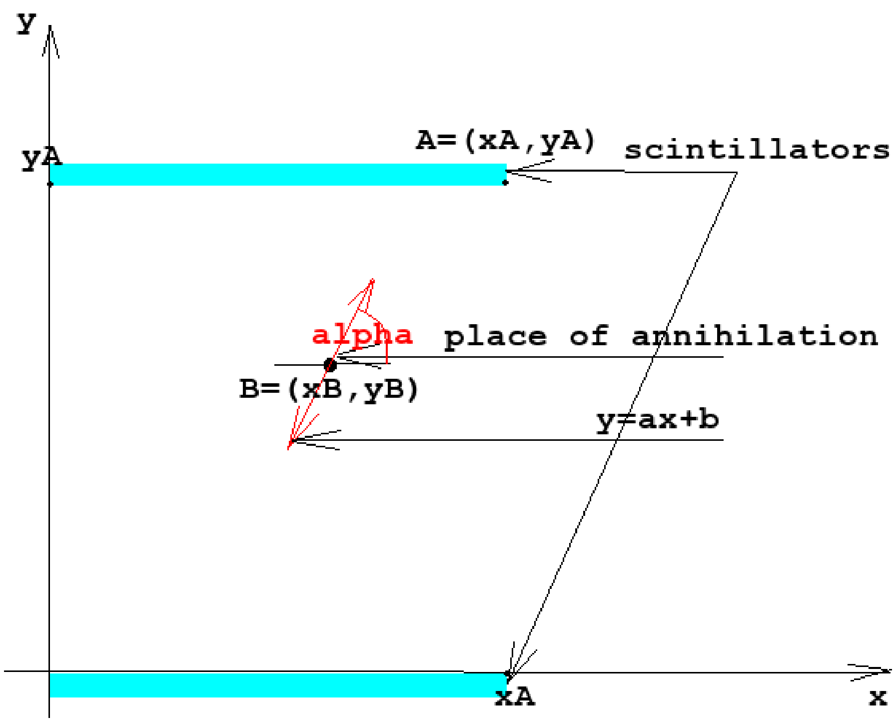
where (r,z) are coordinates of the centre of the pixel

$N_{gen}(r,z)$ – number of generated annihilations inside the pixel with centre (r,z)

$N_{acc}(r,z)$ – number of events (signals in all four photomultipliers)

3. Simulations of 2-detector system

Approximated map of efficiency of 2-detector scanner may be calculated using just geometrical properties of the system and simple MC simulation:

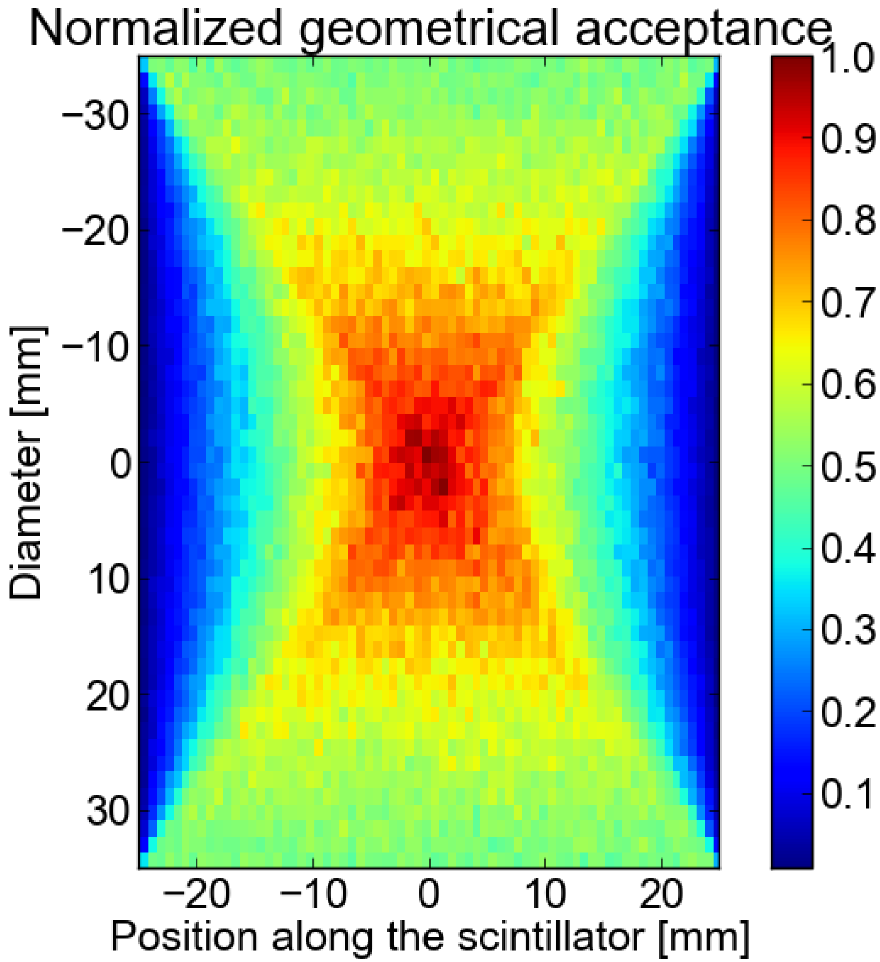


y = ax + b
a = A/B where
A = random(0,1)-0.5
B = random(0,1)-0.5
xB = xA*random(0,1)
yB = yA*random(0,1)
b = yB – a xB
y = a(x-xB) + yB

Points of intersection with the straights 'containing' edges of scintillator:
x1 = (yA-yB)/a + xB
x2 = -yB/a + xB

If x1 is in (0,xA) and x2 is in (0,xA) => point (xB,yB) is added to histogram.

3. Simulations of 2-detector system



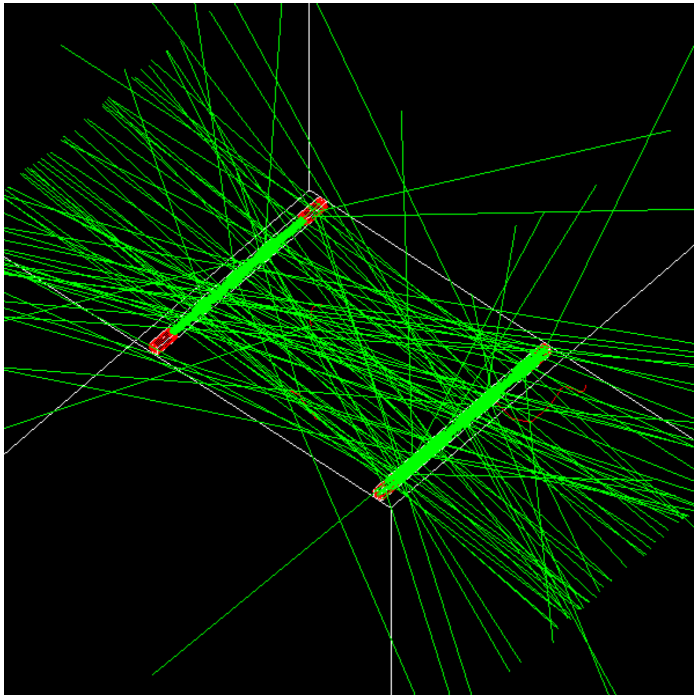
The biggest geometrical acceptance will be observed in the central area of the J-PET tomograph.

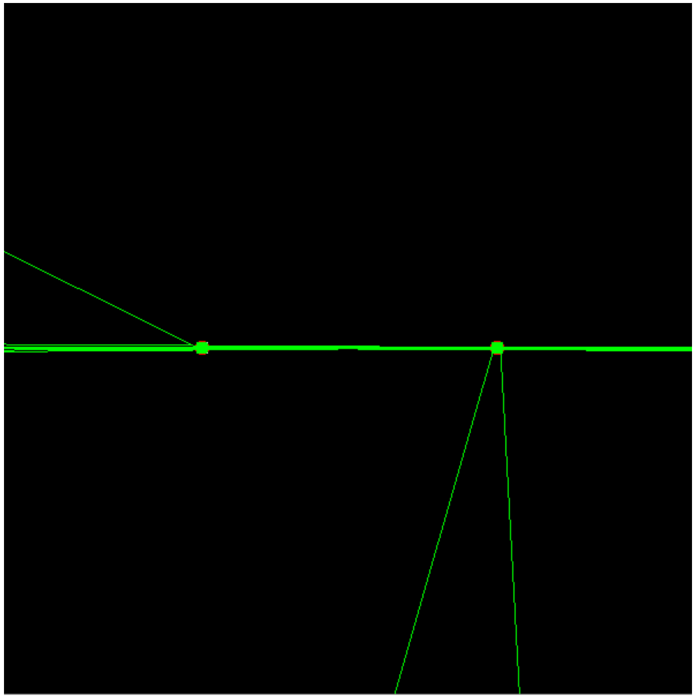
Map of efficiency should include many other effects, like:
- efficiency of scintillators
- efficiency of photomultipliers

etc.

All effects may be included using GATE software.

3. Simulations of 2-detector system

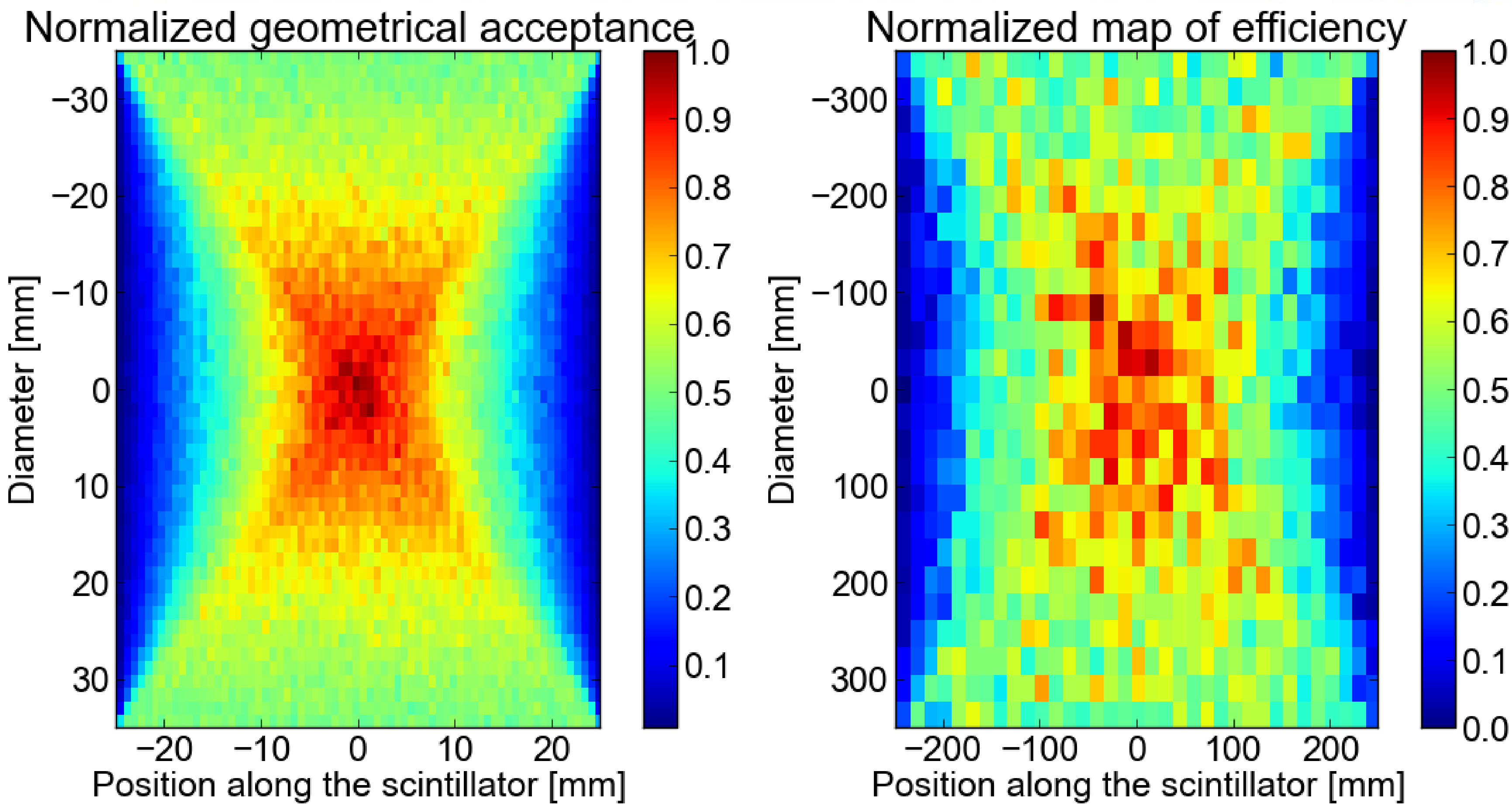




Source:

- back-to-back gamma quanta are emitted from rectangular area 0.5cm x 50cm x 70cm between two plastic scintillators
- solid angles cut to the ranges that provide hits

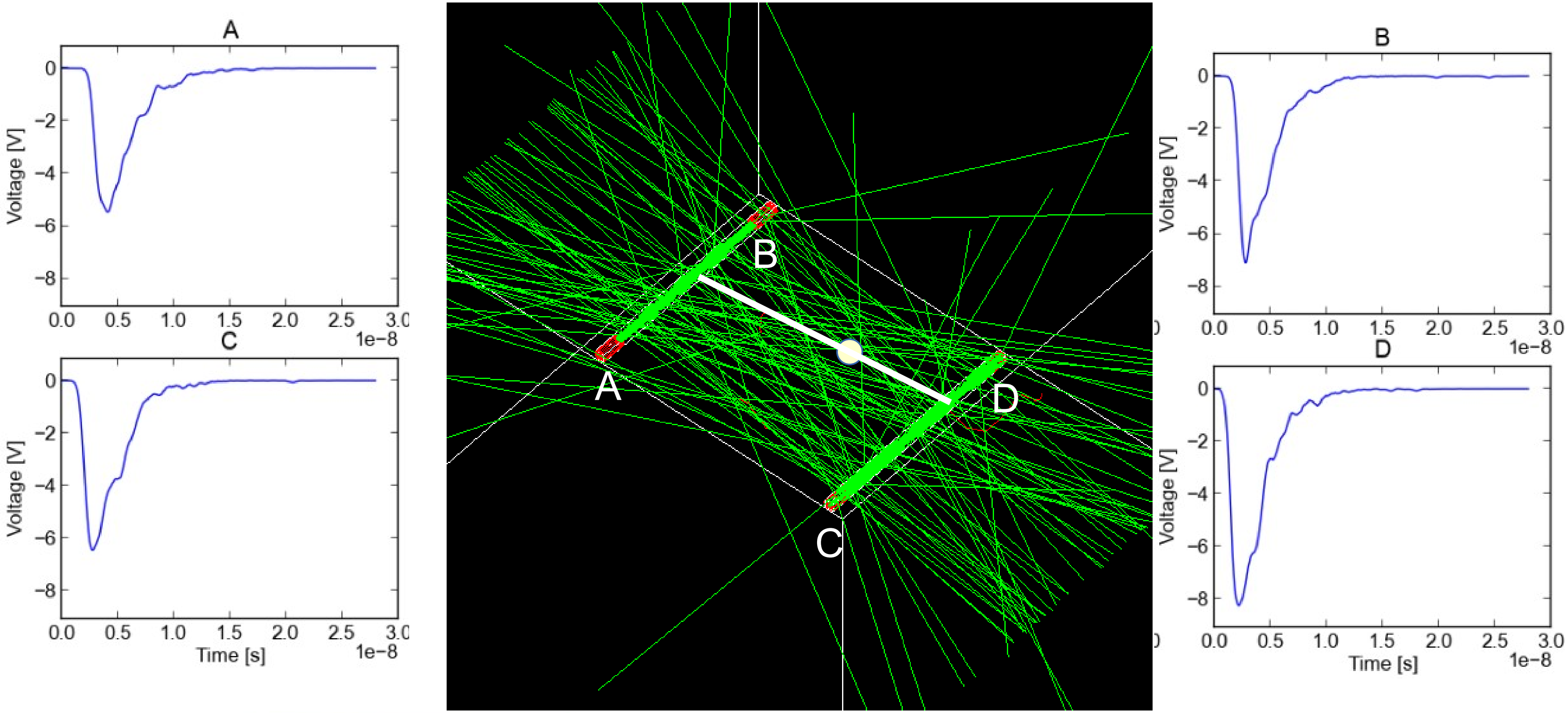
3. Simulations of 2-detector system



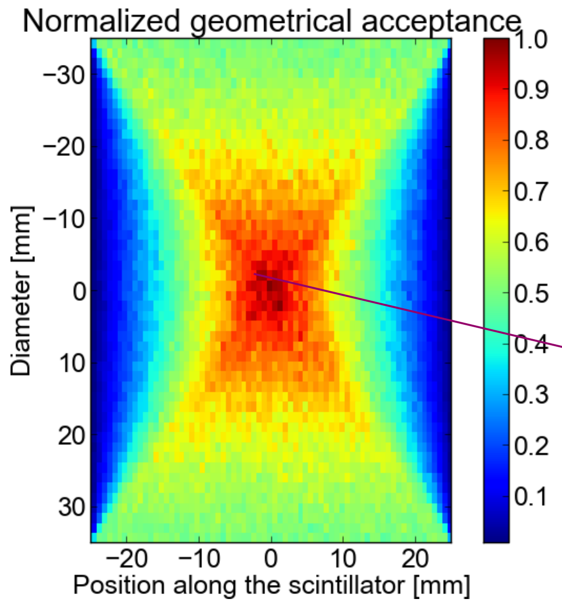
(max. 90 events per bin)

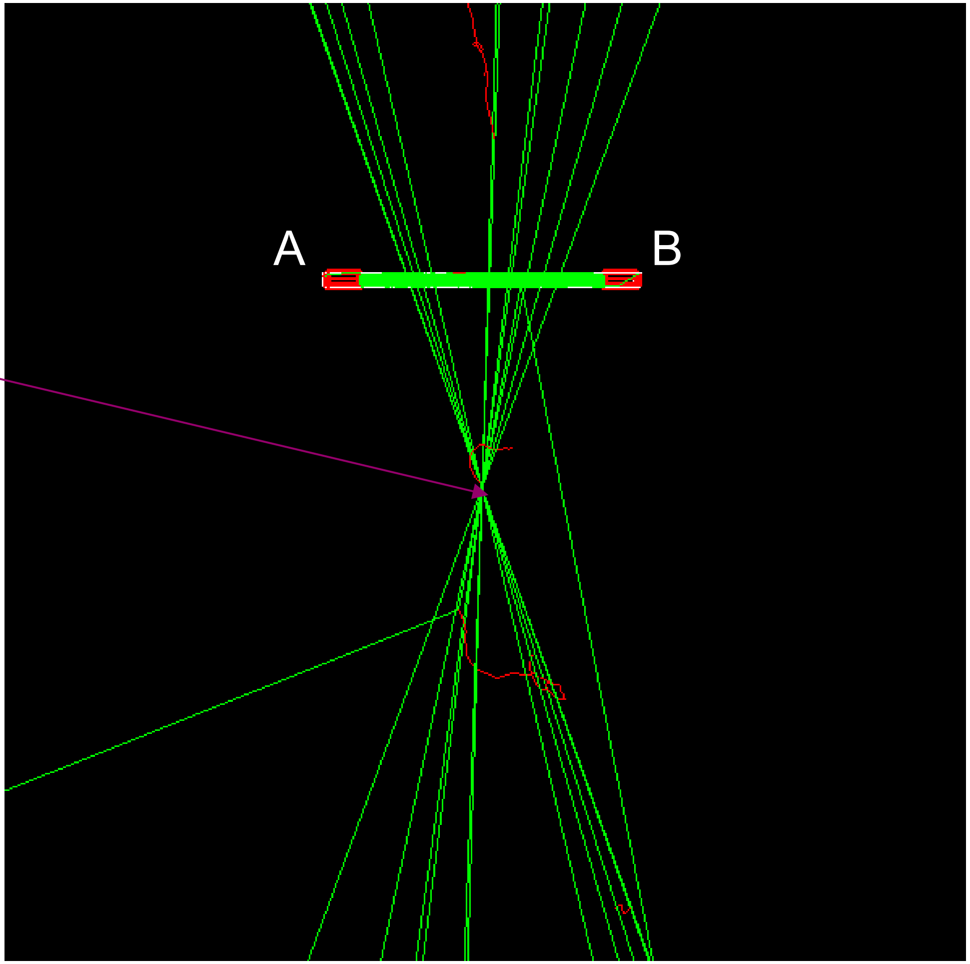
3. Simulations of 2-detector system

For one of coincidences, voltage signals were calculated:



4. Analysis of single detector response to a point source

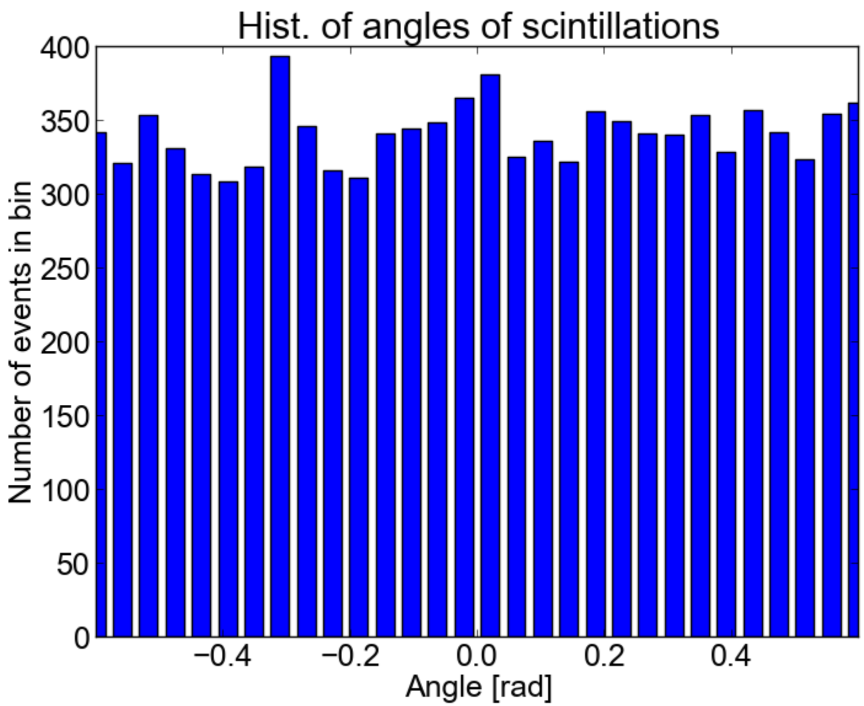


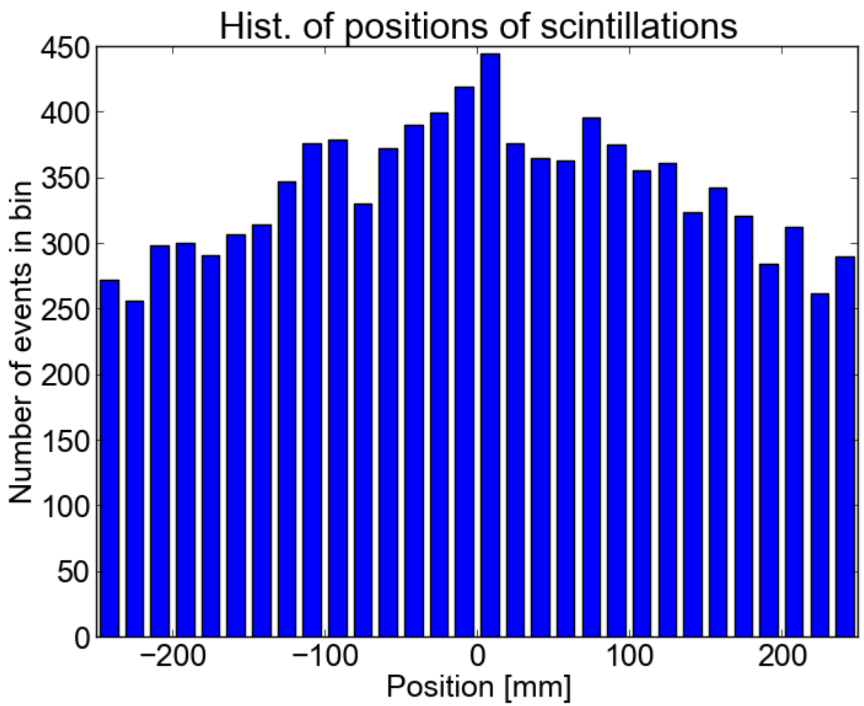


Gamma source:

- point located 35 cm from scintillator
- isotropic angle distribution in limited solid angle

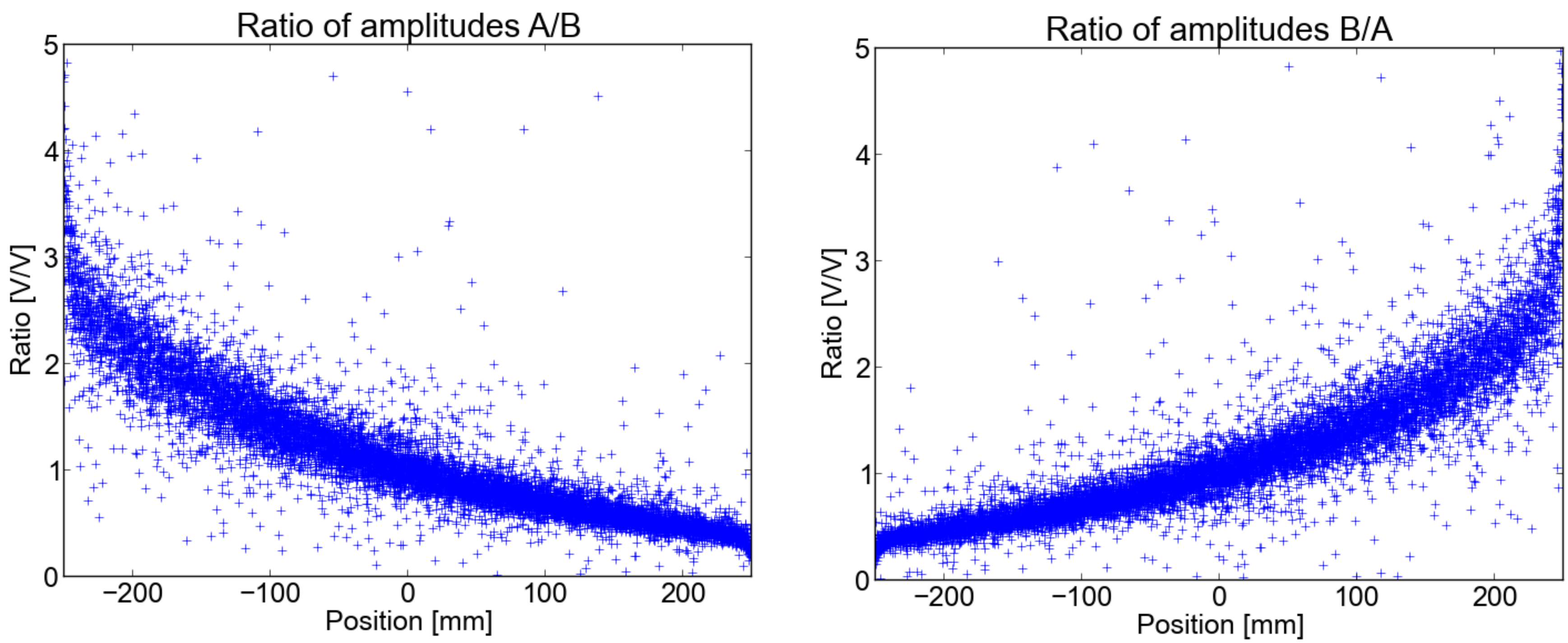
4. Analysis of single detector response to a point source





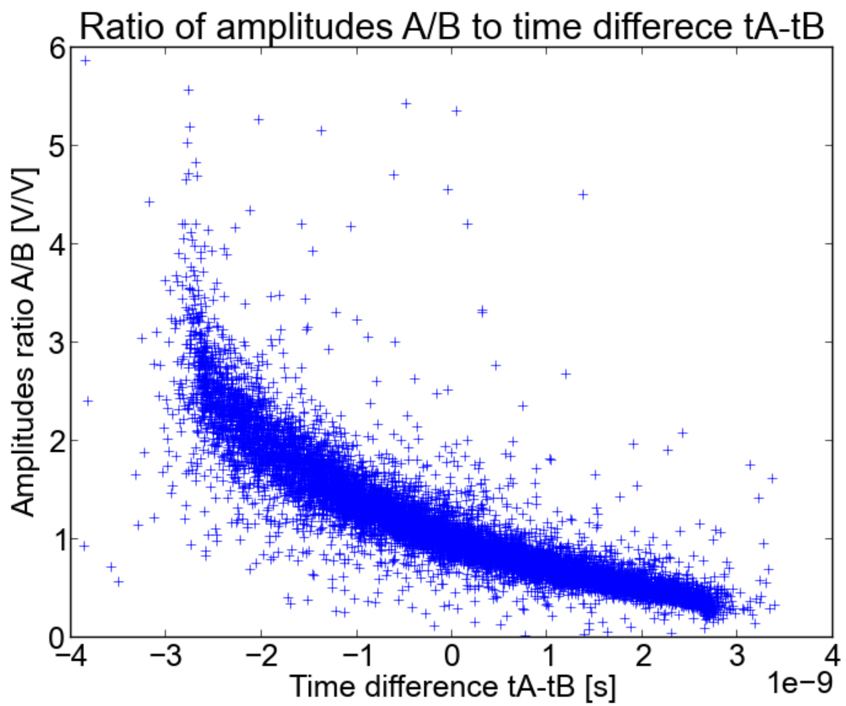
- isotropic angle distribution
- shape of position distribution caused by the geometry of the simulated system

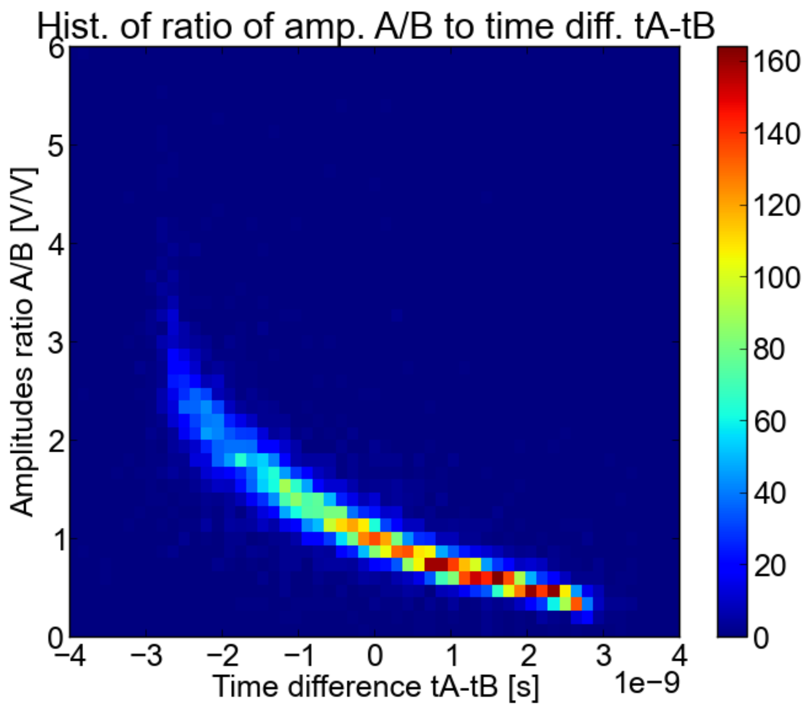
4. Analysis of single detector response to a point source



- the biggest dispersion of amplitudes ratio is for area near to position equal to 0 (dependence is the most flat in this area)

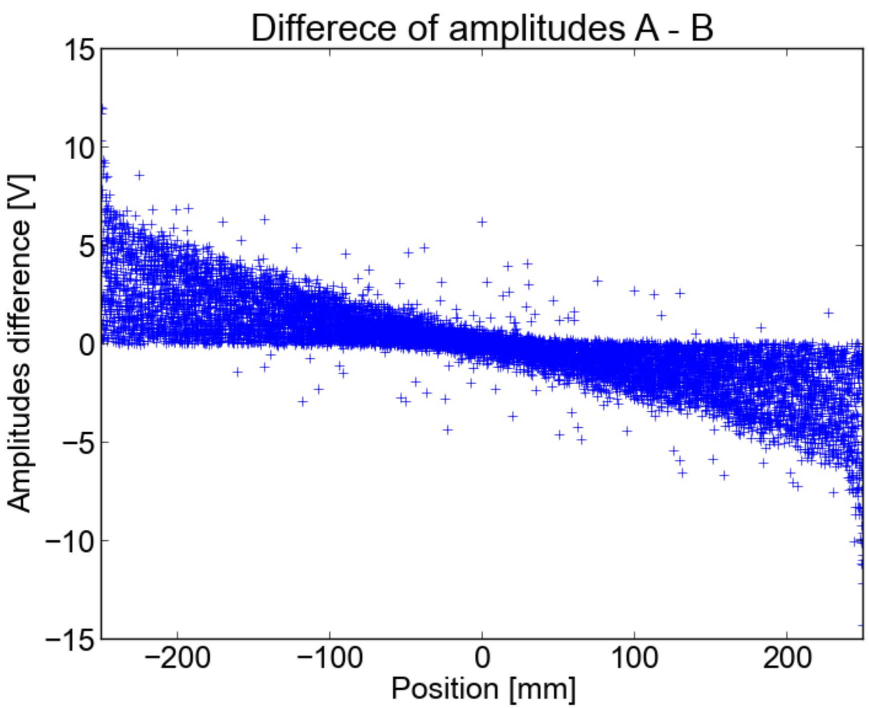
4. Analysis of single detector response to a point source

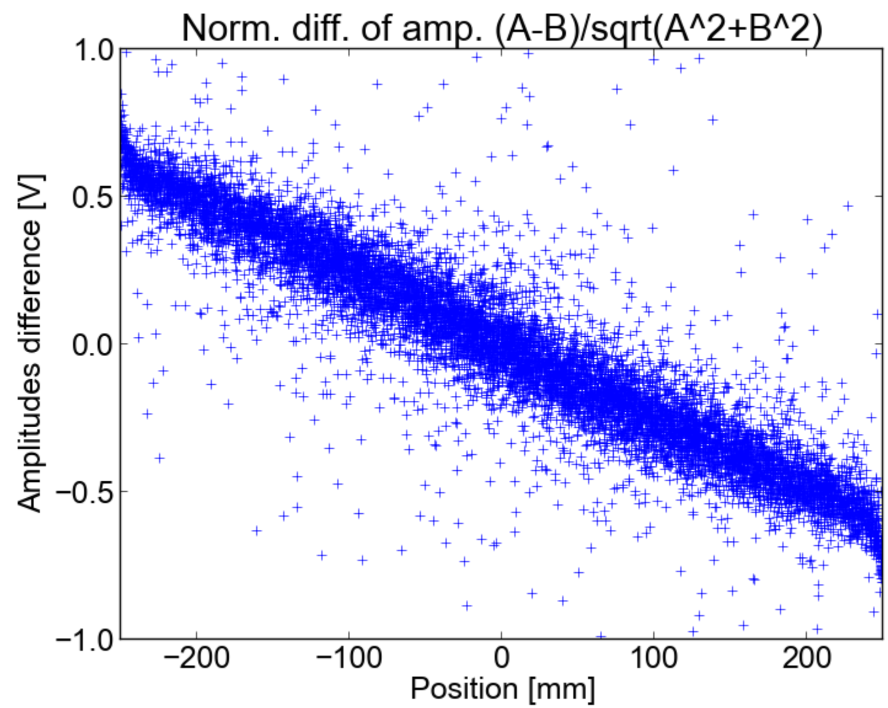




- when time difference is 0 then ratio of amplitudes is about 1 -> simulation works properly

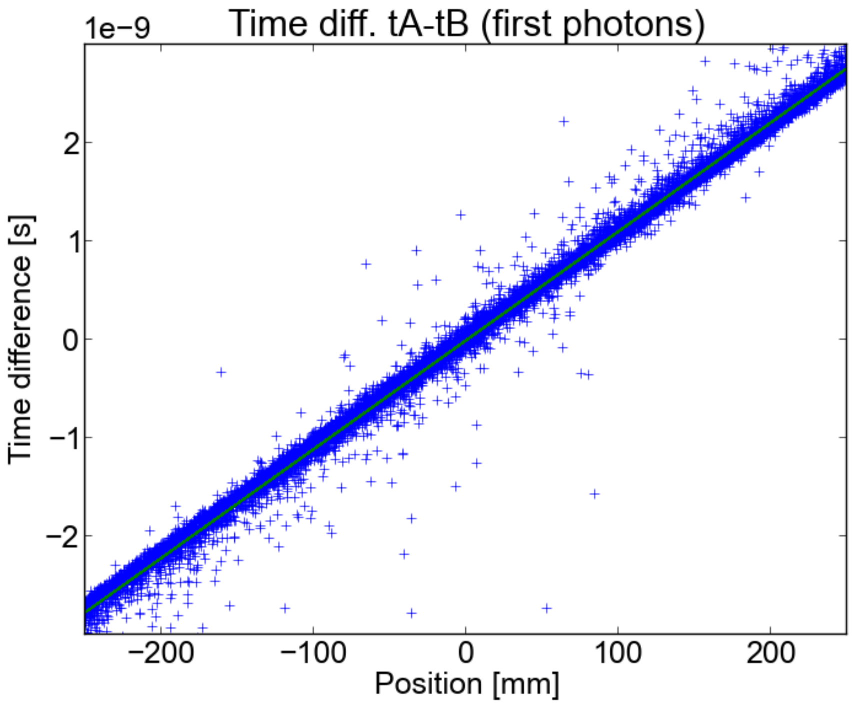
4. Analysis of single detector response to a point source

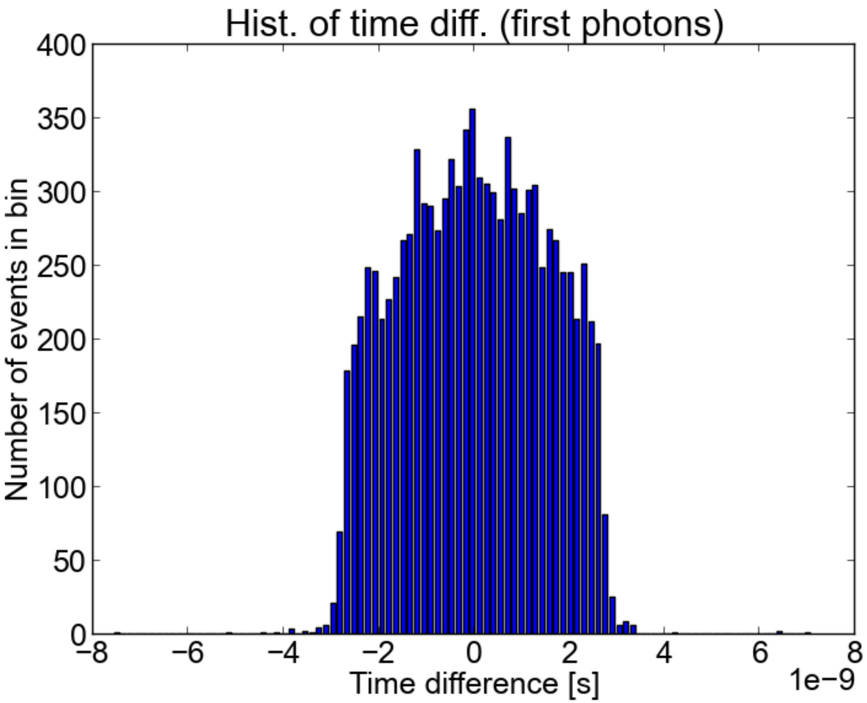




- big value of differences of amplitudes is caused by the fact that all photons (not just optical) are taken into account during calculation of voltage signals
- ratios of amplitudes or normalized difference shouldn't depend on the absolute values of amplitudes

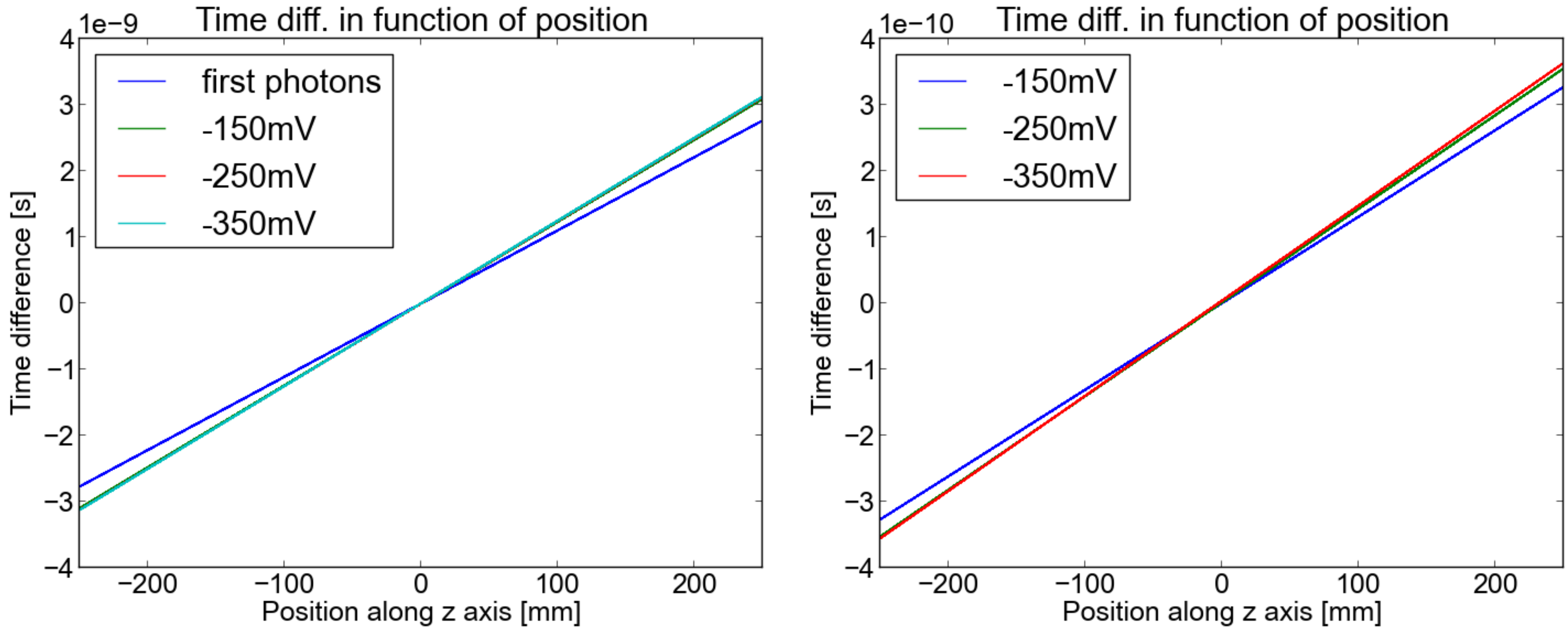
4. Analysis of single detector response to a point source





- time difference is calculated using time information about two photons that reach opposite photomultipliers as first in the signals

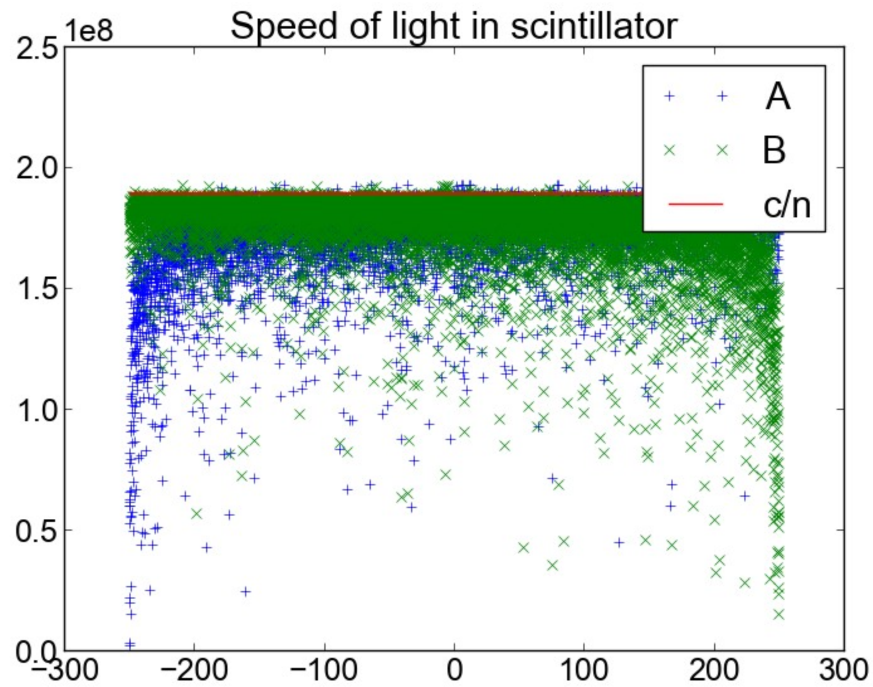
4. Analysis of single detector response to a point source



- it is very important, how time difference is defined
- about 10% difference between time difference calculated using information about first photons or at defined level
- the value of the level is secondary issue

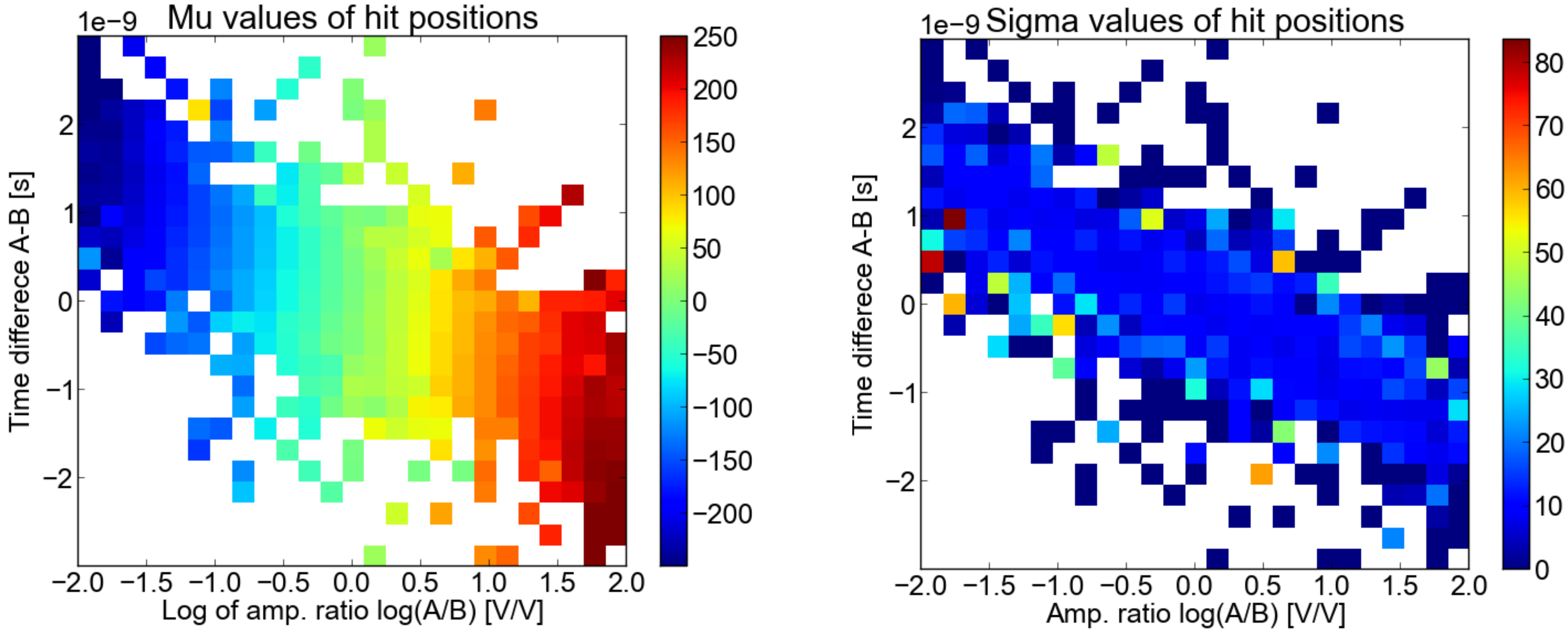
4. Analysis of single detector response to a point source

- “speed of light” was calculated for each photon as a ratio Dd/Dt, where:
  Dd – distance between point of scintillation and the photomultiplier
  Dt – time between moment of scint. and the time of arrival of first photon to pmt
- maximum “speed” limited by the ratio of c/n (n defined in simulation as 1.58)



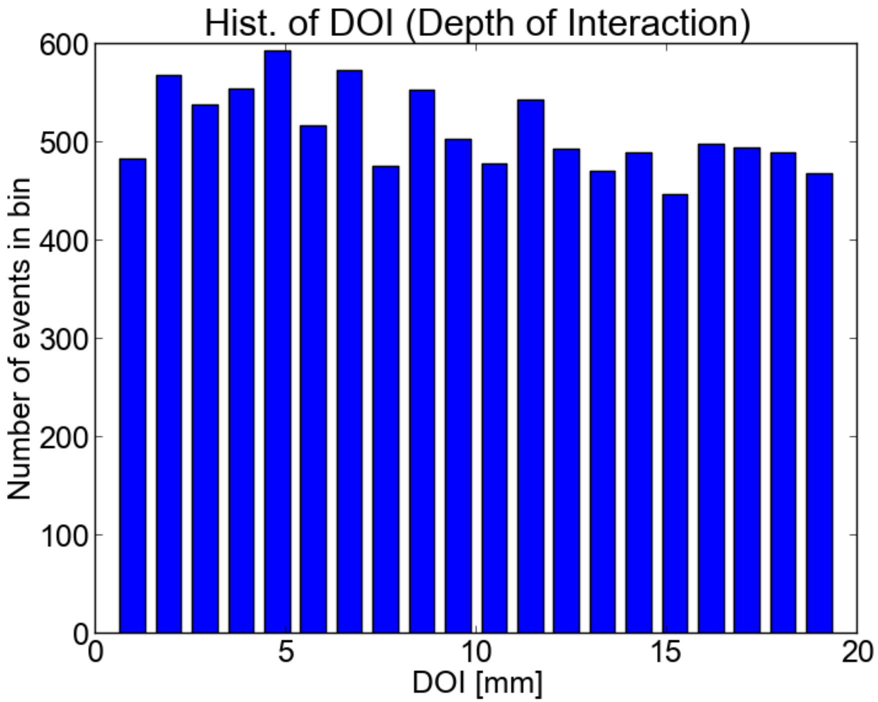
<u>Calculated speed is smaller than c/n ratio because:</u>
- real path is longer than the distance (e.g. cause the reflections)
- in fact, photons are not absorbed in the surface between pmt and scintillator but a part of milimeter before the surface

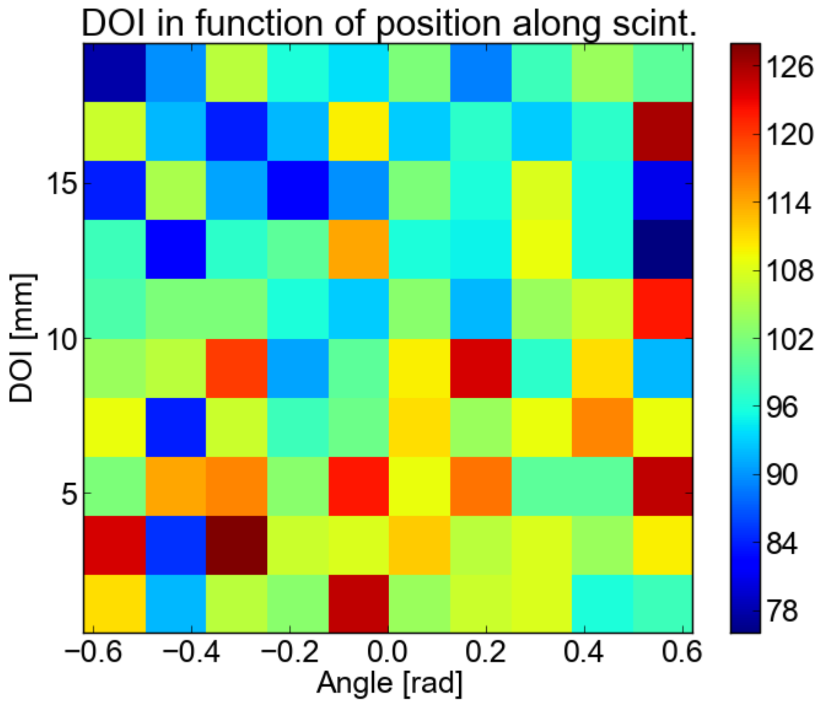
4. Analysis of single detector response to a point source



- space of time difference and logarithm of amplitudes ratio was divided into 25x25 pixels
- in each pixel, for events from this pixel, mean value and standard deviation of position along z axis were calculated

4. Analysis of single detector response to a point source





- the biggest nr of gamma quanta has DOI about 5 mm
- dependence of direction of generation of gamma quanta and DOI is not visible for this statistics

5. Summary

Conclusions:

- Definition of time of the voltage signal is very important for the reconstruction of the place of hit.

- GATE may be simply used to measure Depth of Interaction for different parameters and shapes of the scintillators.

- Covariance matrix may be calculated for system of two photomultipliers using GATE simulation output.

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Thank you for your attention

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