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GEANT4 simulation of gamma ray in a double-gap resistive plate chamber*

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For more than 20 years nuclear physicists have used the GEANT code to simulate particle-matter interaction. In most recent version, GEANT4 is a toolkit for simulating the passage of particles though matter, which contains a complete range of functionality including tracking, geometry, physics models, and hits. In this article, an attempt to use GEANT4 to model a double-gap resistive plate chamber (RPC) with its improved efficiency is presented. The efficiencies of the double-gap RPC have been evaluated as a function of gamma energy range 0.005–1000MeV. A comparison to available previous simulation package GEANT3 data is also performed.

Keywords: GEANT4, Monte Carlo simulation, efficiency, resistive plate chamber
PACC: 2940

1. Introduction

The Monte Carlo code GEANT was first developed in FORTRAN at European Organization for Nuclear Research (CERN) to simulate particle-matter interaction.[1] The new GEANT4 project[2] comes up in 1994 to improve the previous GEANT3 program. The design choice of GEANT4 was an object-oriented methodology and C^{++} language in order to provide a modular and flexible software. All physical processes, models and visualization modules are entirely accessible to the user.

A comparison of simulated results using GEANT3 and GEANT4 electromagnetic physics processes demonstrates that, in general, they are very close to each other. However, in some cases GEANT4 is adequate and its physics is extended beyond GEANT3. In GEANT3 the secondary radiations (x-rays and Auger electrons) from photoelectric effect are not considered. Another weak point of GEANT3 is that it does not simulate a particle when its energy is less than 10keV. GEANT4 can overcome all these difficulties as it includes low-energy electromagnetic processes down to 250eV.[3]

The GEANT4 code is documented with manuals, examples, and experts are available for user support. In this simulation package, the main program constructs a run manager object, as in other GEANT4 applications, which controls the whole simulation process. According to the user's requirements, several classes must be implemented to describe the experimental setup construction (material used, beam line element geometries, detector sensitive components, magnetic and electric fields, particle hits,..), the primary particle generator (primary beam characteristics, such as particle type, kinetic energy distribution, direction distribution, position distribution, ..), the list of particles that can be generated by the simulation and all the associated physics processes.[4]

The last version (version 4.7, released on 12/17/2004) includes very low energy electromagnetic processes, photon evaporation, radioactive decay hadronic processes and high-energy elastic scattering processes (down to tens of eV) to extend the use of GEANT4 to many applications in physics, like space physics and medical physics. Keeping in view the advantages of GEANT4, we decided to develop a simulation package for double-gap resistive plate chamber (RPC) detector in our laboratory using GEANT4 for the first time, so far as we know.

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The development of this simulation package has been done at Institute for Advanced Physics (IAP) on a dedicated Pentium 4 personal computer running CERN Red Hat Linux 7.2.1[5] with the GCC compiler installed 3.2.3, where the last version of GEANT4 and its low-energy extension have been installed. The PC has been entirely interfaced with the C^{++} data analysis environment, An Object-Oriented Data Analysis Framework (ROOT),[6] (data storing, histogramming, fitting,...) developed and available freely at CERN program library. Open Source for Graphics Language (Open GL) and Drawer for Academic Writings (DAWN)[7] drivers have been also installed for online visualization of the simulated interactions.

2. Validation of GEANT4 for RPC detector studies

A study of GEANT4 and its low-energy extension performances was performed on a double-gap RPC detector to validate this simulation package results with the previous GEANT3 simulation results. The RPC was first developed by Santonico and Cardarelli.[8] It consists of two parallel plates, made of phenolic resin (bakelite) with high volume resistivity. A charge Q_0 that enters the resistive electrode surface "decomposes" with time t following an exponential,

$$Q(t) = Q_0 \mathrm{e}^{-t/\tau} \qquad (1)$$

with $\tau = \rho\varepsilon_0\varepsilon_r$, where ρ is the volume resistivity of the material, ε_0 is the dielectric constant and ε_r is the relative permittivity of the resistive material. Typical bakelite resistive plates have a volume resistivity of 10^{10}–$10^{11}\Omega\cdot$cm, leading to a "relaxation time" $\tau \approx 10$ms.[9] The whole structure of RPC is made gas tight. The outer surfaces of the resistive material are coated with conductive graphite paint to form the Higher Voltage (HV) and ground electrodes. The readout is performed by means of copper or aluminium strips separated from the graphite coating by an insulating polyester film (PET) film. Figure 1 shows a schematic image of a double-gap RPC detector used in the simulation code.

The RPCs are the part of compact muon solenoid (CMS) muon sub-detector for the experimentation at the large hadron collider (LHC).[10] They are expected to operate in a hostile environment composed of gamma ray and neutrons. To evaluate the effect of these background radiations on detector functionality, we present an estimation of sensitivity of these detectors to gamma rays in that range. Efficiency of the double-gap RPC has been evaluated as a function of gamma energy in the range of 0.005–1000MeV. Gamma particles were transported by GEANT4 code using standard and low energy electromagnetic processes.

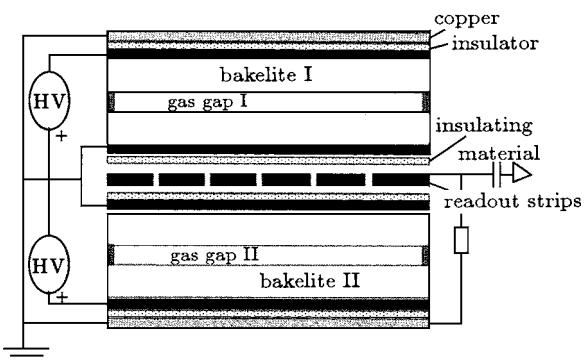


Fig.1. Basic RPC configuration used in the simulation.

2.1. RPC configuration

The detector setup was firstly modelled using the geometrical dimensions supplied by the CMS/RPC environment.[11] The RPC detector structure can be easily described for the simulation program using a variety of geometrical elements available in GEANT4. Moreover, the object-oriented structure of GEANT4 allows the user to define his own classes. One class can be defined as detector construction category for each detector component, such as ground electrode, bakelite, gas gap, etc. They can be combined together to build the entire setup of the RPC detector. A double-gap RPC detector geometric configuration was used (in two single gas gaps with the central common readout strips) with a usual gas mixture of (3% iC_4H_{10} + 97% $C_2H_2F_4$. Here iC_4H_{10} is referred as Iso-butane). which was simulated by the code. A geometric configuration of area 20×20cm^2 double-gap RPC was studied. The detector composition in terms of materials and relative thickness is described in Table 1.

Table 1. Double-gap RPC detector composition.

Material	Thickness/cm	Detector components
Copper (GND)	0.005	External ground shield
Polyethylene	0.060	Gap I Material
Graphite	0.002	Gap I Material
Bakelite	0.2	Gap I Material
Gas (gap I)	0.2	Gap I Material
Bakelite	0.2	Gap I Material
Graphite	0.002	Gap I Material
Polyethylene	0.060	Gap I Material
Strips(copper)	0.005	Central common readout strips
Polyethylene	0.060	Gap II Material
Graphite	0.002	Gap II Material
Bakelite	0.2	Gap II Material
Gas (gap II)	0.2	Gap II Material
Bakelite	0.2	Gap II Material
Graphite	0.002	Gap II Material
Polyethylene	0.060	Gap II Material
Copper (GND)	0.005	External ground shield

2.2. RPC efficiency

In order to obtain the RPC detector response or its efficiency for gamma particle source, we applied the assumption that each produced charged particle generates a signal to the readout strips, on arriving at the RPC gas gap; if more than one charged particles reach the gas gap, only the first one is assumed to generate a signal. The sensitivity ε in our code for a given photon energy is obtained from

$$\varepsilon = N_{\rm i}/N_{\rm o}, \qquad (2)$$

where $N_{\rm o}$ is the number of original primary particles impinging on the RPC detector and $N_{\rm i}$ is the number of charged particles arriving at any of the two gas gaps. In order to obtain a statistical uncertainty of less than 1%, a large number of histories ($> 10^5$–10^6 primary photons) as events simulation were taken into account.

3. Monte Carlo simulation of RPC detector with GEANT4

GEANT4 consists of the following electromagnetic processes needed for gamma-ray spectroscopy namely: Compton scattering, photoelectric effect, Rayleigh effect, pair production, multiple scattering, fluorescence and Auger effect, bremsstrahlung and Ionization. In GEANT4 a new code of electromagnetic interaction for low energy has been developed[12] and its valid energy range is extended down to 250eV. This enhancement is based on the use of experimental data parameterizations and the data base developed by the Lawrence Livermore National Laboratory: EPDL97 (evaluated photon data library). In GEANT MC simulation the relevant physical quantity is the energy deposited into the sensitive detector component, in our case the two gas gaps that are set as sensitive detectors. During the transportation process a photon flux of a definite energy is randomly incident into RPC detector. It travels through detector chamber in the incident direction of the RPC. Here the signals in RPC exposed to photons are expected to be generated by the physics processes (including photoelectric, Compton and pair production, Rayleigh effect etc.,) according to the gamma energy.[13,14] The secondary charged particles lose their energy in the gas gaps. The deposited energy of the charged particle with the signal hits is collected in the event action class. Finally the simulated results can be stored in the histogram using Run action class or Analysis class, where one can manage the histogram file using AIDA[15] or HBOOK.[16] The flowchart of the RPC simulation code has been established, as shown in Fig.2.

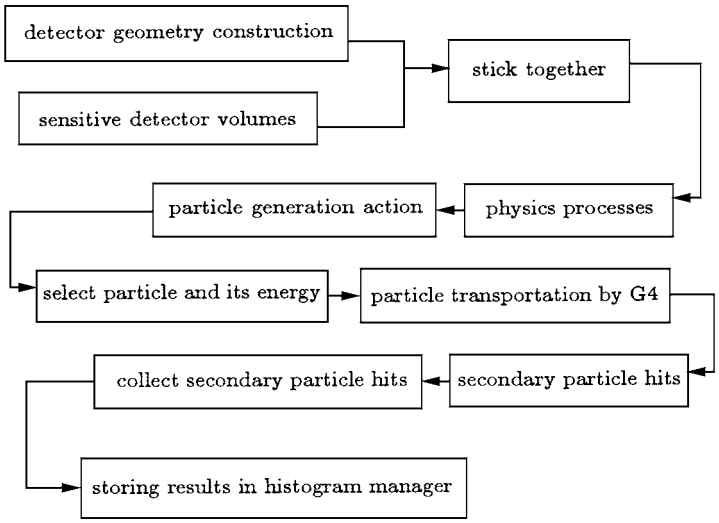


Fig.2. Flow chart of the RPC detector simulation code.

4. Results and discussion

The experimental set-up of the double-gap RPC shown in Fig.1 has been simulated by using the GEANT4 code. In the simulation, the number of gamma particles in the energy range of 0.005–1000MeV randomly strike the RPC. The surface area of the RPC is chosen to be 20cm × 20cm. Two gas gaps of 0.2cm × 0.2cm used as sensitive volumes are uniformly distributed in the RPC. The dimension of the sensitive volume is based on the previous GEANT3 code,[17] consistent with the used sensitive volume dimension.[11] In order to suppress the problems with the physics models, a comparative simulation was carried out using GEANT4 standard electromagnetic physics and GEANT4 low electromagnetic physics (see Fig.3). The results obtained by both of these processes for isotropic gamma source simulation are in good agreement with each other, except for the difference between them that can be seen at energies > 10MeV in Fig.3.

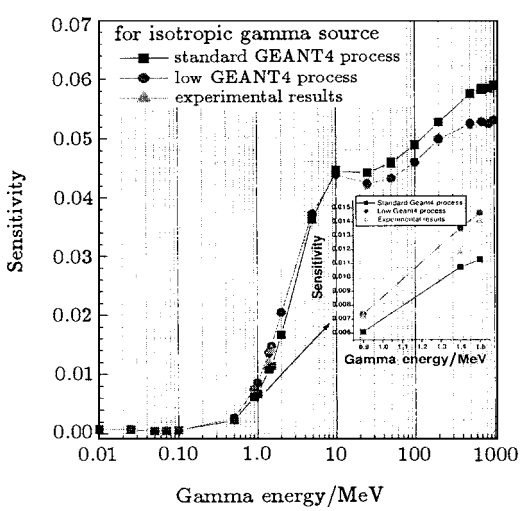


Fig.3. Comparison among the simulated results of GEANT4 standard and low electromagnetic processes, and the measured efficiency for the RPC detector set-up geometry.

On the other hand, to estimate the uncertainties associated with the calculated efficiency, we carry out 10 independent simulations (m=10) for each gamma energy emission. Thus the final calculated efficiency (ε) is given by the mean of the calculated efficiencies (ε_k) for each simulation for a particular energy

$$\varepsilon = 1/m \sum_{k=1}^{m} \varepsilon_k \qquad (3)$$

and the estimation of the variance of the efficiency σ is given by the expression[18,19]

$$\sigma^2 = 1/(m-1) \sum_{k=1}^{m} (\varepsilon_k - \varepsilon)^2. \qquad (4)$$

The obtained results are tabulated in Table 2.

Table 2. RPC detector's mean efficiencies, and their variances for GEANT4 standard and low electromagnetic processes.

Process	Energy/MeV	Mean efficiency ε	Variance of efficiency σ
By GEANT4 standard	0.007	1.50×10^{-5}	0.000008
	0.01	7.78×10^{-4}	0.000098
	0.05	4.48×10^{-4}	0.000078
	0.1	5.48×10^{-4}	0.000093
	0.5	2.20×10^{-3}	0.00012
	0.9	6.00×10^{-3}	0.00065
	1.0	6.50×10^{-3}	0.00023
	1.5	1.11×10^{-3}	0.00027
	2.0	1.60×10^{-2}	0.00035
	5.0	3.60×10^{-2}	0.00069
	10.0	4.40×10^{-2}	0.00084
	25.0	4.40×10^{-2}	0.00053
	50.0	4.50×10^{-2}	0.00080
	100.0	4.80×10^{-2}	0.00073
	200.0	5.20×10^{-2}	0.00065
	500.0	5.70×10^{-2}	0.00701
	700.0	5.80×10^{-2}	0.00084
	1000.0	5.90×10^{-2}	0.00075
By GEANT4 low	0.007	9.00×10^{-6}	0.000008
	0.01	6.91×10^{-4}	0.000075
	0.05	4.47×10^{-4}	0.000054
	0.1	5.03×10^{-4}	0.000007
	0.5	2.60×10^{-3}	0.00016
	0.9	7.30×10^{-3}	0.00013
	1.0	8.40×10^{-3}	0.000328
	1.5	1.40×10^{-2}	0.000269
	2.0	2.00×10^{-2}	0.000609
	5.0	3.70×10^{-2}	0.000495
	10.0	4.30×10^{-2}	0.00082
	25.0	4.20×10^{-2}	0.00085
	50.0	4.30×10^{-2}	0.000595
	100.0	4.50×10^{-2}	0.00064
	200.0	4.80×10^{-2}	0.00010
	500.0	5.23×10^{-2}	0.00080
	700.0	5.26×10^{-2}	0.000463
	1000.0	5.29×10^{-2}	0.00033

Similar studies for parallel gamma source, with gamma beam impinging normally into the RPC were performed. For the double-gap RPC configuration with 2mm gas gap, the present simulated gamma sensitivity results are in agreement with the previous results reported in Ref.[20]. A comparison between the GEANT3 and GEANT4 simulated results[1)] for the RPC detector is shown in Fig.4 and Table 3.

By employing GEANT4 standard electromagnetic process simulation code, the double-gap RPC sensitivity for an isotropic gamma source is $s_\gamma < 5.90\times10^{-2}$ for $E_\gamma < 1000$MeV. For the same gamma source the RPC sensitivity, $s_\gamma < 4.80\times10^{-2}$ at $E_\gamma < 100$MeV has been obtained. Similarly for GEANT4 low electromagnetic process the double gap RPC sensitivity for an isotropic gamma source is $s_\gamma < 5.29\times10^{-2}$ for $E_\gamma < 1000$MeV. The RPC sensitivity for the same gamma source, $s_\gamma < 4.50\times10^{-2}$ at $E_\gamma < 100$MeV has been evaluated. It is evident from the Table 3, that for the isotropic gamma source,

[1)] The results is obtained by employing GEANT4 low electromagnetic packages.

the sensitivity is always greater than for the parallel gamma source; this dependence is due to the fact that the gamma source takes a wider path when it passes through the RPC's bakelite. In the present simulation studies of RPC's setup, a similar effect can be seen. Similar characteristics of RPC sensitivity have been observed for parallel gamma source configuration.

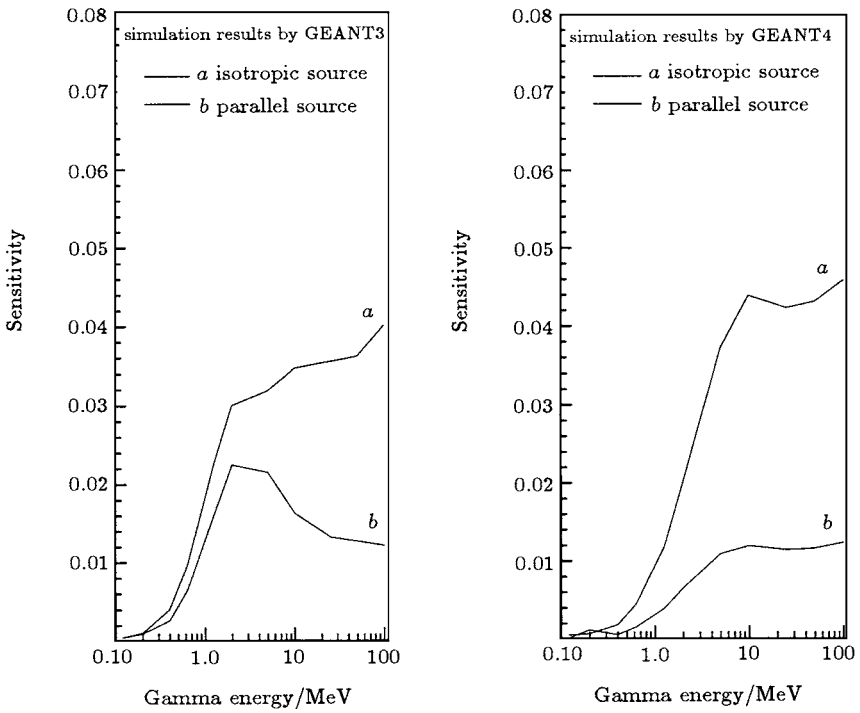


Fig.4. A comparison between double-gap RPC simulated results obtained by GEANT3 and GEANT4 (low electromagnetic packages).

5. Conclusions

A new code for simulation of a double-gap RPC detector based on GEANT4 toolkit for gamma interaction has been presented in this paper. The code has an important intrinsic advantage over existing one for energies below 10keV when energy deposition at microscopic scale is relevant. The code was designed as an extension of a corresponding simulation toolkit GEANT4. Since it makes use of cross-section databases experimentally obtained, complimented with the theoretical calculations, the physics behind the code for gamma interaction can be considered reliable. In its current status, the code is a preliminary version valid to demonstrate its potential capabilities.

In addition, we have simulated with the GEANT4 Monte Carlo code, the efficiency response of RPC detector using GEANT4 standard and GEANT4 low electromagnetic processes for isotropic gamma source. Similarly comparative study of GEANT3 gamma simulated results and GEANT4 gamma simulated results for isotropic and parallel gamma sources has been done as shown in Table 3. A comparison between the simulated and available experimental sensitivity results at low energies is shown in Table 4. From the above results and discussion, we can conclude that the GEANT4 Monte Carlo code is useful for simulating the double-gap RPC detector in a gamma source. The first studies presented in this paper give better confidence and open new prospectives in the simulation of the RPC detector with GEANT4. Authors are currently working on this code to see the detector response for different particle sources.

Table 3. A comparison of RPC simulation results using GEANT3 and GEANT4 for parallel, and isotropic gamma source.

Particles	Energy/MeV	Double-gap RPC sensitivity	
		By GEANT3	By GEANT4*
γ isotropic	0.1	4.80×10^{-4}	5.39×10^{-4}
	1.0	1.70×10^{-2}	0.84×10^{-2}
	5.0	3.19×10^{-2}	3.70×10^{-2}
	10.0	3.40×10^{-2}	4.30×10^{-2}
	25.0	3.50×10^{-2}	4.20×10^{-2}
	50.0	3.80×10^{-2}	4.30×10^{-2}
	100.0	4.00×10^{-2}	4.50×10^{-2}
γ parallel	0.1	4.60×10^{-4}	1.45×10^{-4}
	1.0	1.20×10^{-2}	0.28×10^{-2}
	5.0	2.10×10^{-2}	1.00×10^{-2}
	10.0	1.60×10^{-2}	1.20×10^{-2}
	25.0	1.30×10^{-2}	1.14×10^{-2}
	50.0	1.27×10^{-2}	1.16×10^{-2}
	100.0	1.22×10^{-2}	1.26×10^{-2}

Table 4. Summary of the experimental, and simulated gamma sensitivity results.

Particles	Energy/MeV	Double-gap RPC sensitivity		
		Experimental results	GEANT3 results	GEANT4 results[a]
γ	0.9	0.72×10^{-2}	0.92×10^{-2}	0.73×10^{-2}
	1.4	1.18×10^{-2}	1.60×10^{-2}	1.30×10^{-2}
	1.5	1.40×10^{-2}	1.90×10^{-2}	1.46×10^{-2}

[a]Statistical errors are within 1%, while the GEANT4 results refer to the results obtained by employing GEANT4 low electromagnetic process.

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