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GEANT4 code for Simulation of neutrons for a double-gap Resistive Plate Chamber

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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 Monte Carlo code to watch a double-gap Resistive Plate Chamber's (RPC) response to neutrons is presented. The simulation calculations of the double-gap RPC have been evaluated as a function of neutron energy in the range 1×10^{-10} MeV-10 GeV. For an isotropic neutron source using GEANT4 standard Electromagnetic Process MC code, sensitivity, $s_n < 2.547 \times 10^{-2}$ at < 1 GeV by double-gap RPC has been observed. For the same neutron source with GEANT4 Low Electromagnetic Process MC code double-gap RPC sensitivity, $s_n < 2.557 \times 10^{-2}$ at < 1 GeV has been measured. Similar characteristics of the RPC detector have been observed for parallel neutron source configuration. In addition, a comparison of the current GEANT4 double-gap RPC detector neutron simulation results with the GEANT3, and with the available experimental results is performed.

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1. Introduction

The GEANT4 [1] Monte Carlo radiation transport toolkit provides the basic services and infrastructure required for the development of flexible simulation frameworks and applications which have found generalized use in high energy physics, nuclear physics, astrophysics and medical physics. GEANT4 Object-oriented design provides the possibility to implement or modify any physics processes in GEANT4 without changing other parts of the software. This feature makes GEANT4 open to extension of its physics modeling capabilities and to the implementation of alternative physics models. Additional factors responsible for the increasing use of GEANT4 are modularity, a flexible infrastructure and the Low Energy Electromagnetic Physics Processes category, which provide alternative models for electron and photon transport down to 250 eV [2]. Keeping in view the advantages of GEANT4, we developed a simulation code (i.e an application of GEANT4) for the double-gap RPC detector in our laboratory for the first time. The development of this simulation package has been done at the Institute for Advanced Physics (IAP) on a dedicated Pentium 4 personal computer running CERN Red Hat Linux 7.2.1.

Studies on the CMS [3] and a toroidal for LHC apparatus (ATLAS) [4] have shown that the RPCs and other detectors at the LHC will operate in an intense radiation background mostly made of photons, neutrons and charged hadrons. RPCs, and each detector in the CMS experiment, will work in a hostile environment rich of neutrons and gamma rays. The maximum expected fluxes in the muon detector for neutrons and gammas are around 5×104 and 1×104 cm^2s^{-1}, respectively, for the CMS ME1 station (Endcap region). While fluxes one order of magnitude lower are expected in the MB1 station (Barrel region).

For evaluating the effect of this background radiation on the detector functionality, it is essential to know the RPC sensitivity for this kind of radiation. Neutron background, in an energy range between 20 meV (thermal neutrons) and 1 GeV, is produced from the hadronic interactions in the calorimeter and from the interactions of the primary proton beam with the beam pipe and/or the beam collimators, while gamma radiation is mainly due to neutron radiative capture and inelastic scattering. For the gamma radiation case the energy range could be between 40 keV and 10 MeV.

In order to understand how these kinds of background could affect the detector functionality, we need to know the detector sensitivity to these kinds of radiation. The motivation of our studies is to estimate the double-gap RPC configuration sensitivity response to neutrons in the range 10^{-10} MeV to 10 GeV. Neutrons were simulated in the RPC double-gap three-dimensional geometry by means of GEANT4 Monte Carlo code. In the following, we present the measurement results on neutron RPC sensitivity as a source of low energy neutrons (mostly below En < 20 MeV) and high energy neutrons (mostly above En > 20 MeV).

2. GEANT Monte Carlo codes

As the scale and the complexity of high energy physics experiments increase, simulation studies require more and more care and become essential to design and optimize the detectors, to develop and test the reconstruction and analysis programs, and to interpret the experimental data. GEANT is a system of detector description and simulation tools that help physicists in such studies. The Geant3 [5] program was written to describe the passage of particles through matter. Originally designed for high energy physics experiments, it has also found applications outside this domain in the area of medical and biological sciences, radioprotection and astronautics. The first version was released in 1971 and the system was developed with some continuity over 20 years till the last release Geant3.21 in 1994. It has become a popular and widely used tool in the HEP community. In the previous RPC background simulation studies reported in [6, 7, 8, 9, 10, 11] the Geant3.21 Monte Carlo code was used giving reliable results.

GEANT4 offers an ample set of complementary and alternative physics models based either on theory, on experimental data or on parameterizations. In particular, GEANT4 provides Packages specialized for modeling both electromagnetic and hadronic physics interactions. The Geant4 electromagnetic Packages handle the electromagnetic interactions of leptons, photons and ions. Especially they include multiple scattering, ionization, bremstrahlung, positron annihilation, photoelectric effect, Compton and Reyleigh Scattering, gamma conversion, synchrotron and transition radiation, Cernekov effect, refraction, absorbtion, scintilatiuon, fluoresence, Auger effect, Particle Induced X-ray Emission (PIXE) [1]. In the present studies, we present the results concerning the following Geant4 electromagnetic Packages:

- Standard Energy Package;
- Low Energy Package, based on Livermore data Libraries [12, 13, 14].

2.1 GEANT4 Standard Energy Package

The standard Package [1] provides a variety of models based on analytical approach to describe the interactions of electrons, positrons, photons, and charged hadrons in the energy range between 1.0 keV to 100 TeV. These models assume that the atomic electrons are quasi-free (i.e., their binding energy is neglected for all particle interaction processes except the photoelectric effect) while the atomic nucleus is fixed (i.e., the recoil momentum is neglected). The Geant4 Standard Package is mainly addressed to the high energy physics domain.

2.2 GEANT4 Low Energy Package

The Low Energy Package [1, 15] extends the range of accuracy of electromagnetic interactions down to lower energy than the Geant4 Standard Package. This Low Energy Package approach exploits evaluated data libraries (EPDL97 [12], EEDL [13] and EADL [14]) which provide data for the calculation of the cross-sections and the sampling of the final state for the modeling of photon and electron interactions with matter. The current implementation of low energy electron processes can be used down to 250 eV. This Package handles the ionization by hadrons and ions [16, 17]. It adopts different models depending on the energy range and the particle charge.

3. RPC Specific Configuration

The detector geometry is described by creating a hierarchy of the different elements and specifying their positions and orientations. Using these strategies, and the geometrical dimensions supplied by the CMS/RPC environment we modeled, the RPC detector setup. The RPC detector structure can be easily described to the simulation program utilizing a variety of geometrical elements available in GEANT4. Additionally 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. These classes can be combined together to build the entire setup of double-gap RPC detector. A double gap RPC detector geometry configuration was used in (two single gas gaps with the central common readout strips) with a usual gas mixture of (3%i C_4H_{10}+ 97% $C_2H_2F_4$) which, was simulated by the Geant4 Monte Carlo code. In this present GEANT4 Monte Carlo Simulation work a geometrical configuration of area 20 × 20 cm^2 double-gap RPC was studied. Double-gap RPC detector composition in terms of materials and relative thickness is described in Table 1.

Two Different kinds of neutron sources were chosen for this simulation study:

- An isotropic source of neutrons, evenly distributed on the RPC chamber surface,
- A parallel source of neutrons, perpendicularly impinging on the whole RPC's surface.

For each source configuration, the sensitivity was evaluated at 29 different energies: 1×10^{-10}, 10^{-9}, 10^{-8}, 10^{-7}, 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}, 10^{-1}, 0.5, 1, 1.4, 1.5, 2, 5, 10, 25, 50, 100, 200, 250, 500, 700, 1000 MeV, 2 GeV, 5 GeV, and 10 GeV. In this simulation work, the range threshold for secondary particles (i.e., for γ, $e-$, and $e+$) production in electromagnetic processes was set to 1 μm, 1nm, and 1μm respectively.

3.1 RPC detector's response to neutrons using Geant4Monte Carlo Code

The geometrical setup of the double-gap RPC detector tabulated in Table.1, has been simulated by the Geant4 code. A primary beam of neutrons with definite energy is randomly incident into RPC detector, which transports all kinds of particles involved in the simulation application. Signals in the RPC detector exposed to neutrons are expected to be produced by a variety of nuclear processes (i.e., elastic scattering, in-elastic scattering, radioactive capture, and so on [18]) depending on the neutron energies. Double-gap RPC detector response which is well known as "RPC sensitivity"is a function of the incoming particles energy, since at different energies different processes are responsible for the secondary particles production. For the evaluation of double-gap RPC sensitivity to neutrons, in the present 20×20 cm^2 RPC chamber surface, we applied the same upper limit assumption reported in [7, 8] i.e., that each produced charged particle generates a signal into the readout strips on arriving at the gas gaps; if more than one charged particles reaches the gas gap, only the first one is assumed to produce a signal. It is important to note that in the present simulation study, only those signals due to neutrons that enter the RPC detector contribute to the neutron sensitivity.

Table 1: Double-gap RPC Detector's Composition.

Material	Thickness(cm)	Detector components
Copper	0.005	External ground shield
Ployethylene	0.060	Gap I Material
Graphite	0.002	Gap I Material
Bakelite	.2	Gap I Material
Gas (gap I)	.2	Gap I Material
Bakelite	.2	Gap I Material
Graphite	0.002	Gap I Material
Ployethylene	0.060	Gap I Material
Strips(Copper)	0.005	Central common read-out strips
Ployethylene	0.060	Gap II Material
Graphite	0.002	Gap II Material
Bakelite	.2	Gap II Material
Gas (gap II)	.2	Gap II Material
Bakelite	.2	Gap II Material
Graphite	0.002	Gap II Material
Ployethylene	0.060	Gap II Material
Copper	.005	External ground shield

The sensitivity in our code is defined as: sens = N_I/N_0, where N_I is the total number of charged particles arriving at any of the two gas gaps and N_0 is the total number of original primary particles impinging upon the RPC chamber.

4. Discussions and Results

The simulation program for a neutron source is more complex than for a gamma source as it implies the use of the neutron interaction cross sections for several nuclei and several energies [7]. At higher energies it works very well, however at low energies, to estimate accurately the neutron interaction cross sections by using GEANT3.21 Monte Carlo code becomes rather difficult. In case of Geant4 application code for RPC detector it works very effectively both for low and high energy neutron simulation. RPC neutron sensitivity results can be seen in Fig. 1, which were obtained by Geant4 Standard and Geant4 Low electromagnetic Packages. In addition, we applied both of these Geant4 Packages to the RPC detector configuration in order to reject the problem of Physics models. The obtained results both of these processes for the isotropic neutron source, and for parallel neutron source are in good agreement except at lowest energies (i.e, En <10 MeV). It is evident from Fig. 1, that for an isotropic neutron source, the sensitivity values are higher than the parallel neutron source. This dependence is due to the fact that neutrons passing isotropically through the RPC will have a larger and wider path than for the case of the parallel neutron source. Therefore, neutrons impinging isotropically on the RPC surface will generate more charged particle signals, which cause more signals to be detected by the strips. Hence, the isotropic neutron source sensitivity is higher for the parallel neutron source. The sensitivity values rise in the low energy region (En < 1×10^{-5} MeV) which is mostly due to γ's coming from the (n,γ) capture reaction whose cross section increases with the decrease in neutron energy as $\sigma \propto 1/\sqrt{En}$.

The detector response uniformity has been studied by computing each neutron energy efficiency fluctuation around the average. To estimate the uncertainties associated to the calculated efficiency, we simulated 10 independent runs (i.e m=10) of the Monte Carlo simulation code for each flux of neutrons at definite energy. The final calculated efficiency (ε) is given by the mean of the efficiencies (εk) calculated for each simulation run at particular energy, and the estimation of the variance of the efficiency σ is given by the expression [19, 20].

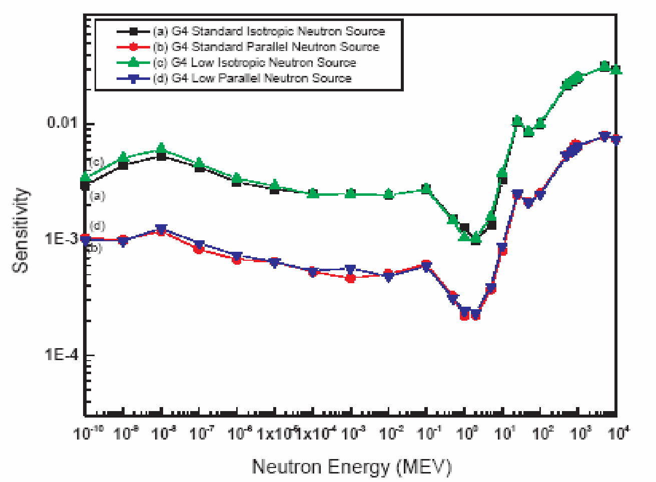

Figure 1: Comparison of GEANT4 Standard and Low electromagnetic processes and measured efficiency for the RPC detector set-up geometry.

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

$$\sigma_{\varepsilon}^{2} = 1/(m-1) \sum_{k=1}^{m} (\varepsilon k - \varepsilon)^{2} \qquad (2)$$

The obtained results can be seen in Table 2.

Similar simulation studies for parallel neutron source by employing both Geant4 Standard and Geant4 Low electromagnetic Packages were performed. For the double gap RPC configuration with 2mm gas gap, the present neutron sensitivity results are in agreement with the previous results [21]. A comparison between the Geant3.21 and Geant4 neutron simulation results for the RPC detector is shown in Table 3.

Employing Geant4 Standard electromagnetic Packages the double-gap RPC sensitivity for an isotropic neutron source is $s_n < 2.547\times10^{-2}$ for En < 1 GeV, while applying Geant4 Low electromagnetic Packages the RPC sensitivity, $s_n < 2.557\times10^{-2}$ has been found for the same energy domain. Similarly for the double-gap RPC using parallel neutron source for Geant4 Standard electromagnetic Packages the neutron sensitivity $s_n < 6.368\times10^{-3}$ has been noted for for En ≈ 1 GeV.

Whereas the RPC neutron sensitivity, $s_n < 6.496\times10^{-3}$ for the same neutron source, and energies has been obtained using the Geant4 Low electromagnetic Packages. The present Geant4 neutron simulation results are reliable and are in agreement with the experimental results reported in [7, 9, 10]. A comparison between the simulated and available experimental neutron sensitivity results at low energies can be seen in Table 4.

5. Conclusions

The first simulation study was performed for neutron RPC sensitivity measurement using Geant4 Monte Carlo code. With the present Geant4 Monte Carlo code for a double gap RPC detector neutrons in the energy range of 10^{-10} MeV to 1 GeV were simulated. For this simulation application, all geometrical configurations and materials of the RPC were implemented. By watching the sensitivity results obtained for the RPC detector both by Geant4 Standard, and by Geant4 Low electromagnetic packages “it has been shown that ”this application code works very effectively both for low and high energy neutrons. Therefore one can conclude that Geant4 simulation, demonstrates, once more, to be a powerful instrument to understand the physical mechanism underlying RPC operation.

We hope that the present simulation studies could be an efficient instrument for evaluating critical parameters of the design of a standard double gap RPC detector to be used in future for the construction of CMS muon sub-detector in the LHC (Large Hadron Collider), at CERN, Geneva. The simulation method illustrated here could be used to estimate detector response (sensitivity) for different experimental environments according to various neutron energy spectra shown in Fig. 2, we estimated the RPC sensitivity with isotropic neutron source; the spectra of the first charged particles (e^-′s, e^+′s, protons, and α) crossing both of the gas gaps are super-imposed. We calculated total neutron sensitivity directly from the ratio of spectral areas; the obtained results are reported in Table 5. According to our calculated results, CMS MB1 chamber will have a hit rate due to neutrons about 0.6 Hz /cm^2.

Table: 2 RPC mean efficiencies, and their variance for GEANT4 Standard and Low processes[*].

Particles Source	Energy (MeV)	GEANT4 Standard		GEANT4 Low	
		ε	σ	ε	σ
isotropic neutron	10^{-10}	$2.96 * 10^{-3}$	0.000179	$3.148 * 10^{-3}$	0.000234
	10^{-8}	$5.334 * 10^{-3}$	0.000178	$6.064 * 10^{-3}$	0.000169
	10^{-7}	$4.224 * 10^{-3}$	0.000186	$4.545 * 10^{-3}$	0.000268
	10^{-6}	$2.744 * 10^{-3}$	0.000141	$2.927 * 10^{-3}$	0.000134
	10^{-4}	$2.505 * 10^{-3}$	0.000127	$2.48 * 10^{-3}$	0.000240
	10^{-2}	$2.44 * 10^{-3}$	0.000129	$2.442 * 10^{-3}$	0.000145
	10^{-1}	$2.738 * 10^{-3}$	0.000155	$2.720 * 10^{-3}$	0.000150
	1.0	$1.263 * 10^{-3}$	0.000178	$1.045 * 10^{-3}$	0.003110
	2.0	$9.96 * 10^{-4}$	0.000297	$1.032 * 10^{-3}$	0.002457
	5.0	$1.341* 10^{-3}$	0.000781	$1.573 * 10^{-3}$	0.000161
	10.0	$3.353 * 10^{-2}$	0.000148	$3.771 * 10^{-3}$	0.000087
	25.0	$1.048 * 10^{-2}$	0.000389	$1.054 * 10^{-2}$	0.004710
	50.0	$8.574 * 10^{-3}$	0.000354	$8.069 * 10^{-2}$	0.000336
	100.0	$1.004 * 10^{-2}$	0.000142	$1.012 * 10^{-2}$	0.003060
	250.0	$1.409 * 10^{-2}$	0.000223	$1.405 * 10^{-2}$	0.000502
	500.0	$2.168 * 10^{-2}$	0.006800	$2.190 * 10^{-2}$	0.000354
	1000.0	$2.547 * 10^{-2}$	0.004596	$2.557 * 10^{-2}$	0.000435
	5000.0	$3.142 * 10^{-2}$	0.000743	$3.149 * 10^{-2}$	0.000272
	10,000.0	$2.922 * 10^{-2}$	0.000448	$2.888 * 10^{-2}$	0.000446
parallel neutron	10^{-10}	$1.035* 10^{-2}$	0.000352	$1.002* 10^{-2}$	0.000128
	10^{-8}	$1.119* 10^{-3}$	0.000084	$1.263* 10^{-2}$	0.000181
	10^{-7}	$8.30* 10^{-4}$	0.000065	$9.360*10^{-4}$	0.000990
	10^{-6}	$6.450* 10^{-4}$	0.000800	$6.440* 10^{-4}$	0.000060
	10^{-4}	$5.310* 10^{-4}$	0.000082	$5.440* 10^{-4}$	0.000094
	10^{-2}	$5.070* 10^{-4}$	0.000008	$4.820* 10^{-4}$	0.000059
	10^{-1}	$6.150* 10^{-4}$	0.001915	$5.940* 10^{-4}$	0.000093
	1.0	$2.20* 10^{-4}$	0.000000	$2.430* 10^{-4}$	0.000044
	2.0	$2.22* 10^{-4}$	0.000052	$2.340* 10^{-4}$	0.00000
	5.0	$3.70* 10^{-4}$	0.000043	$3.950* 10^{-4}$	0.000057
	10.0	$7.950* 10^{-4}$	0.000064	$8.880* 10^{-4}$	0.000107
	25.0	$2.448* 10^{-3}$	0.000126	$2..510* 10^{-3}$	0.000196
	50.0	$2.118* 10^{-3}$	0.000148	$2.109* 10^{-3}$	0.000100
	100.0	$2.537* 10^{-3}$	0.000927	$2.470* 10^{-3}$	0.000105
	250.0	$3.378* 10^{-3}$	0.000189	$3.551* 10^{-3}$	0.000291
	500.0	$5.458* 10^{-3}$	0.000210	$5.359* 10^{-3}$	0.000160
	1000.0	$6.368* 10^{-3}$	0.000263	$6.496* 10^{-3}$	0.000181
	5000.0	$7.946* 10^{-3}$	0.000312	$7.955* 10^{-3}$	0.000439
	10,000.0	$7.410* 10^{-3}$	0.000326	$7.312* 10^{-3}$	0.000227

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[*] statistical errors are within 1%.

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

Particle Source	Energy (MeV)	Double-gap RPC Sensitivity	
		By GEANT3	By GEANT4 Standard
isotropic neutron	10^{-3}	0.00235	0.00249
	10^{-2}	0.00227	0.00244
	1.0	0.00178	0.00126
	2.0	0.0016	0.00096
	5.0	0.00189	0.00134
	10.0	0.00305	0.00335
	25.0	0.00989	0.01048
	50.0	0.00991	0.00857
	100.0	0.00519	0.01004
	250.0	0.00416	0.01409
	500.0	0.00318	0.02168
	1000.0	0.00301	0.02547
parallel neutron	10^{-3}	0.00083	0.000465
	10^{-2}	0.00136	0.000507
	1.0	0.0007	0.00022
	2.0	0.00089	0.00022
	5.0	0.00115	0.00037
	10.0	0.001	0.00079
	25.0	0.00506	0.00244
	50.0	0.00316	0.00211
	100.0	0.00222	0.00253
	250.0	0.00177	0.00337
	500.0	0.00159	0.00545
	1000.0	0.00151	0.00673

Table 4: Summary of the experimental and simulated neutron sensitivity results[†].

Particles	Energy (MeV)	Double-gap RPC sensitivity		
		Experimental Results	G4 Standard Results	G4 Low Results
neutrons	1.0	$2.0 * 10^{-3}$	$1.263 * 10^{-3}$	$1.045 * 10^{-3}$
	2.0	$6.3 * 10^{-4} \pm 0.02$	$9.6 * 10^{-4}$	$1.023 * 10^{-4}$
	20.0	$5.3 * 10^{-3} \pm 0.5$	$5.88 * 10^{-3}$	$5.62 * 10^{-3}$
	50.0	$<7\text{-}80 * 10^{-3}$	$8.20 * 10^{-3}$	$8.60 * 10^{-3}$

Table 5: RPC sensitivity estimated with CMS RB1 neutron spectrum.

For RPC area 20 * 20 (cm^2)		
	By Geant4 Standard Package	By Geant4 Low Package
Sensitivity	$3.45 * 10^{-3}$	$3.724 * 10^{-3}$
Hit Rate (Hz cm^2)	0.483	0.521

[†] statistical errors are within 1%.

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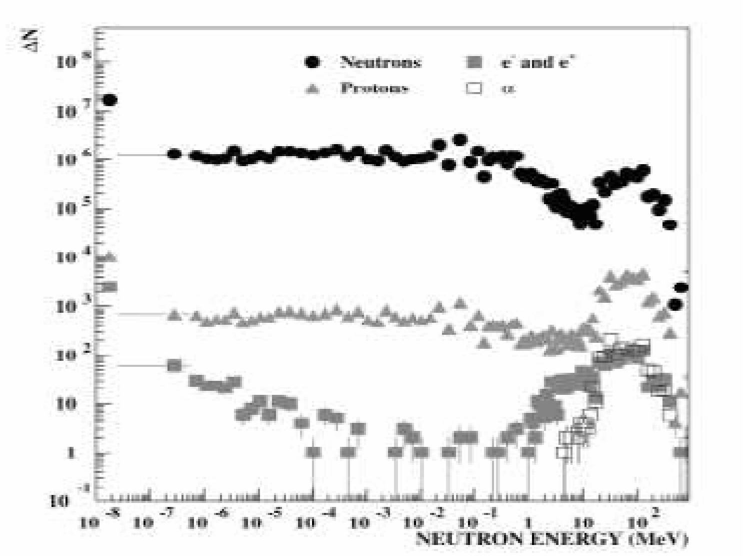

Figure 2: CMS Muon Barrel (MB1) neutron spectrum (full circles) that enters the RPC.

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