SIMULATION OF BREMSSTRAHLUNG RADIATION IN TUNGSTEN USING GEANT4

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Abstract

This study explores the generation of Bremsstrahlung radiation by electrons in tungsten (W) targets of varying thicknesses subjected to different energy beams using GEANT4 simulations. By systematically modifying the target thickness and electron beam energies, we examine the resultant radiation yield and spectrum. The results enhance our understanding of Bremsstrahlung processes in high-Z materials and provide valuable insights for applications such as radiation therapy, particle detectors, and material analysis.

Keywords: Bremsstrahlung Radiation, GEANT4 Simulation, Tungsten Targets, Electron Beam, Radiation Yield

Introduction

Bremsstrahlung radiation, often referred to as braking radiation, is a fundamental phenomenon in the field of high-energy physics and material science. It occurs when high-speed electrons decelerate upon encountering the electric fields of nuclei within a material, emitting radiation as a result. The efficiency of Bremsstrahlung radiation production is notably higher in materials with a high atomic number (Z), such as tungsten (W), due to the stronger electric fields surrounding these heavier nuclei.

Tungsten, in particular, is a material of significant interest for Bremsstrahlung studies due to its high density and high atomic number, which make it an efficient bremsstrahlung radiator. This makes it an ideal target material for applications such as X-ray production, particle detectors, and radiation shields.

The GEANT4 toolkit, a software package developed for simulating the passage of particles through matter, offers robust capabilities for modeling complex interactions such as Bremsstrahlung radiation[1]. Utilizing Monte Carlo methods, GEANT4 can simulate interactions at the atomic level, providing detailed insights into the physics of particle deceleration and photon emission. This allows for a comprehensive analysis of the Bremsstrahlung process, taking into account factors such as the energy of the incident electron beam and the geometric configuration of the target material.

In recent studies, the GEANT4 simulation has been validated against experimental data, demonstrating its capability to accurately replicate Bremsstrahlung radiation spectra. For instance, Sempau et al. (2003) have shown that GEANT4 can provide reliable predictions of Bremsstrahlung yields under various conditions, thereby underscoring the code's utility for both scientific research and practical applications in medical and industrial fields[2].

In the context of this study, GEANT4 is employed to simulate Bremsstrahlung radiation in tungsten targets. By altering the electron beam energy and the thickness of the tungsten targets, the simulation can provide valuable data on the resultant radiation spectrum. This data is crucial for optimizing the design and operation of equipment that relies on Bremsstrahlung radiation, ranging from medical imaging devices to particle accelerators[3].

Theory

The theory underpinning Bremsstrahlung radiation is deeply rooted in quantum electrodynamics (QED), which describes the interactions between light (photons) and charged particles (such as electrons). When an electron passes close to the strong electric field near the nucleus of an atom, the field exerts a force on the moving electron, causing it to decelerate and change direction. According to the laws of electrodynamics, any charged particle that accelerates emits radiation; this is the radiation observed as Bremsstrahlung.

The differential cross-section for Bremsstrahlung production when an electron with initial energy E is scattered by the nucleus can be approximated in the non-relativistic limit by the following formula derived from the Bethe-Heitler theory[4]:

$$\frac{d\sigma}{dk} = \frac{Z^2\alpha^3\hbar^2}{m_e{}^2c^4}\frac{1}{k}\left(\frac{E}{E-k} + \frac{E-k}{E} - \frac{2}{3}\frac{k^2}{E(E-k)}\right) \quad (1)$$

where:

- $\frac{d\sigma}{dk}$ is the differential cross-section per unit photon energy (k),
- Z is the atomic number of the nucleus,
- α is the fine-structure constant,
- $\hbar$ is the reduced Planck's constant,
- m_e is the electron mass,
- c is the speed of light,
- E is the initial energy of the electron,
- k is the energy of the emitted photon.

The above equation describes the emission spectrum of the photons, which is continuous up to a maximum energy that equals the initial energy of the electron. In relativistic cases, where the energy of the electrons is comparable to or greater than its rest mass energy, the formula becomes more complex, incorporating additional terms and relativistic corrections.

The total cross-section for Bremsstrahlung production can be obtained by integrating the differential cross-section over all possible photon energies[5]:

$$\sigma = \int_{k_{min}}^{E} \frac{d\sigma}{dk} dk \qquad (2)$$

In practice, the calculation of Bremsstrahlung radiation requires numerical methods and complex QED models that account for various corrections, including screening effects, electron spin, and exchange effects[6]. These calculations are embedded within the physics models of Monte Carlo simulation codes like GEANT4, which allow for the detailed study of Bremsstrahlung in various materials and geometries.

Simulation

The simulation process with GEANT4 is a multi-step procedure that involves a detailed setup of the experimental conditions, including the geometry of the target and the materials involved, the definition of the particle beam, and the setup of the detector system. In the context of using the TestEm5 example from the GEANT4 package, this process can be expanded as follows:

The first step involves setting up the basic components required for the simulation. This includes initializing the run manager, which controls the flow of the simulation, and the various managers for geometry, physics, and other aspects of the simulation. The TestEm5 example comes with predefined initializations that can be adapted for specific needs[1].

The geometry of the experimental setup is crucial as it dictates the physical space through which the particles will move and interact. In TestEm5, the geometry is defined through a combination of solids, logical volumes, and physical volumes that represent the target material and surrounding environment. For simulating Bremsstrahlung radiation in tungsten targets, one would define a solid with the dimensions of the tungsten slab and assign the appropriate material properties to it.

The beam of electrons is defined in terms of energy, position, and direction. In the context of TestEm5, this is done using a particle gun that can be configured to emit electrons with specific energies, mimicking the conditions of the actual experiment. Beam parameters are often set in the macro (.mac) files, allowing for easy adjustment and repetition of simulations under different conditions.

The detector material needs to be specified to record the Bremsstrahlung photons generated by the electron beam interaction with the tungsten target. This involves defining the detector geometry and materials in a similar manner to the target geometry, ensuring that the simulation can track and record the relevant data.

The choice of physics processes is essential for an accurate simulation. GEANT4 provides a variety of physics lists that include models for electromagnetic interactions, hadronic interactions, and decay processes. For Bremsstrahlung, the electromagnetic processes are most relevant, and the TestEm5 example includes physics lists that can model the production of Bremsstrahlung photons by electrons.

Macro files in GEANT4 are scripts that set up the initial conditions and parameters for the simulation run. They can be used to specify the energy and direction of the electron beam, the number of events to simulate, and the recording of the simulation data. For the TestEm5 example, these '.mac' files can be customized to investigate the impact of different electron energies and target widths on the production of Bremsstrahlung radiation[7].

Once all the parameters are set, the simulation is executed by running the macro files through the GEANT4 executable. The TestEm5 example will simulate the passage of electrons through the target material and record the resulting Bremsstrahlung photons, tracking their energy and momentum.

The output of the simulation typically includes data on the energy spectrum of the emitted photons, the angular distribution, and the total yield of Bremsstrahlung radiation. This data can be analyzed to draw conclusions about the efficiency of Bremsstrahlung production for different target configurations and beam energies.

By employing the TestEm5 example as a base, researchers can modify the macro files and geometry definitions to tailor the simulation to their specific research questions regarding Bremsstrahlung radiation in tungsten targets.

Analyzing the provided GEANT4 run summary data, we can derive some key results and insights into the behavior of electrons when passing through a Tungsten (W) target. The data presented shows the results of a simulation run with 123 electrons of 30 MeV energy each, interacting with a 1 cm thick Tungsten target. Below is an analysis of the key points from this data, along with a table summarizing the findings.

Energy Deposition:

- The total energy deposit in the absorber per event is 4.074 MeV with a standard deviation of 93.46 keV.
- This indicates a mean energy loss (dE/dx) of 4.074 MeV/cm or 1.748 MeV*cm²/g in tungsten.

Leakage:

- Primary leakage (energy not deposited in the target) averages 23.65 MeV with a standard deviation of 399.8 keV.
- Secondary leakage (energy from secondary particles) averages 2.17 MeV with a standard deviation of 319.2 keV.
- The total energy balance (edep + eleak) is 29.89 MeV, which is close to the initial total energy of the electrons (30 MeV).

The detailed information for this simulation is provided in the Table 1.

Table 1. Simulation parameters after run.

Parameter	Value	Standard Deviation
Total Energy Deposit (MeV/event)	4.074	93.46 keV
Mean dE/dx (MeV/cm)	4.074	-
Primary Leakage (MeV/event)	23.65	399.8 keV
Secondary Leakage (MeV/event)	2.17	319.2 keV
Total track length - charged (cm)	1.138	244.4 µm
Total track length - neutral (cm)	4.53	505.1 µm
Multiple scattering - rms (mrad)	141.6	-
Multiple scattering - θ_0(mrad)	133.3	-
Steps - charged (per event)	29.41	1.439
Steps - neutral (per event)	1.154	0.1041

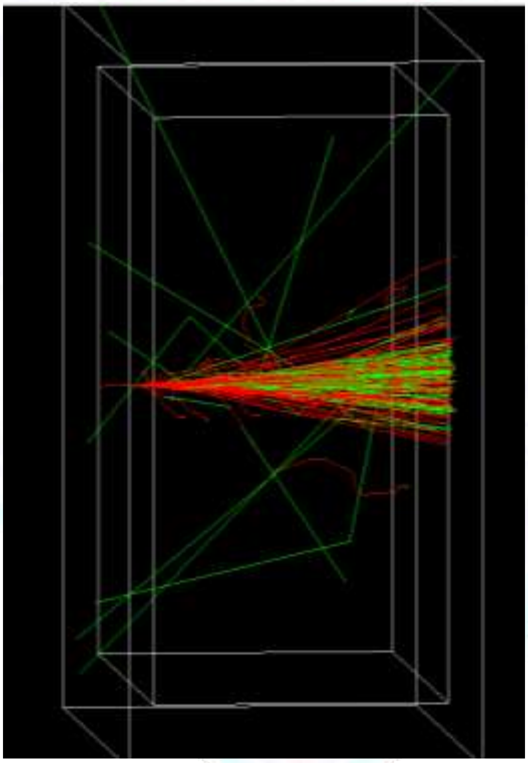

Figure 1. Running the simulation

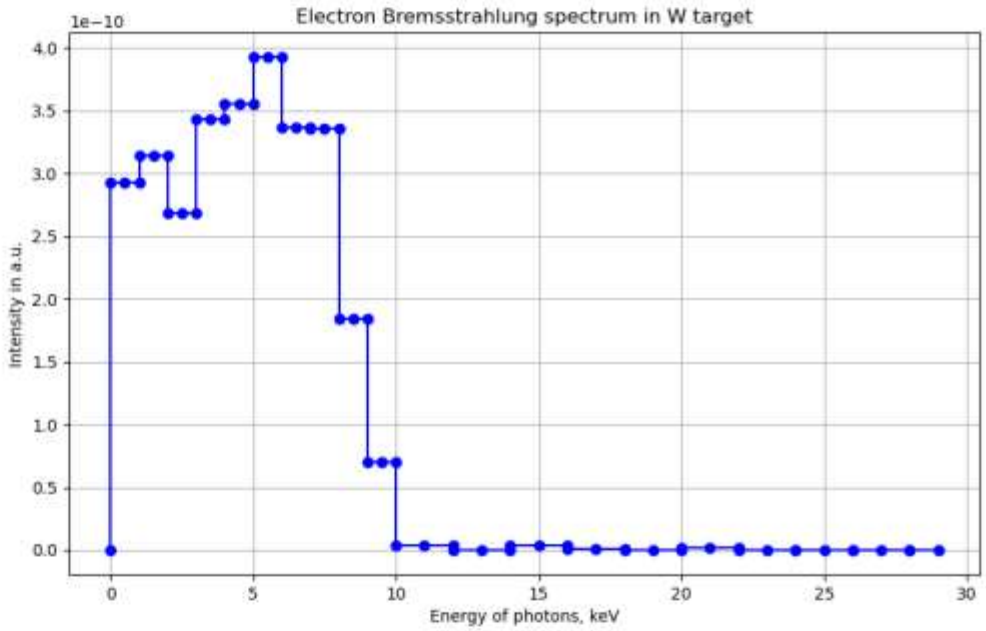

Figure 2. Bremsstrahlung spectrum of electrons in W target

Conclusions

Higher-Z materials (like tungsten) show more significant interactions (higher energy deposition) for electrons, as expected due to their higher density and atomic number. The energy deposition pattern varies significantly depending on both the incident particle type and the target material. The leakage energy is a critical parameter, especially in high-energy physics experiments, as it indicates the amount of energy not deposited in the target. This is crucial for understanding the particle's behavior post-interaction (Figure 2).

These findings have applications in various fields, including: Particle Physics: Understanding particle interactions with different materials is crucial for designing detectors and other experimental setups. Medical Physics: Particularly in radiotherapy, where understanding how different particles deposit energy in tissues is essential. Material Science: For understanding radiation damage and other effects of high-energy particles on materials.

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