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Monte Carlo optimization of a Compton suppression system for gamma-ray diagnosis of combustion plasma

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ABSTRACT

The use of Gamma-ray spectrometers provides very important diagnostic tools in large-scale tokamak experiments. In this study, the Geant4 toolkit was used to simulate a Compton suppression system based upon a High-Purity Germanium (HPGe) primary detector in order to gain the optimal sizes for the construction of the system for 0.1 MeV–10 MeV γ-rays which are emitted from the HL-2A tokamak. BGO crystal is selected for the anti-coincidence secondary detector. Simulation results show that when the closer the HPGe primary detector is set to the beam entrance and the smaller the entrance size is, the higher the Compton Suppression Factors (CSFs) are. Moreover, adding a BGO crystal to the back of the HPGe detector can also improve the CSFs, and the CSFs increase more significantly with the higher γ-ray energies. And a BGO crystal with the thickness of 25 mm in front of the HPGe detector can reach a good suppression effect. For the BGO hollow cylinder, the CSFs do not increase obviously after its thickness reaches 60–70 mm. Finally, optimal parameters for the Compton suppression system are suggested. Moreover, for the optimal Compton suppression system, γ-rays produced by neutrons which are also one of fusion products, can be well suppressed.

1. Introduction

As an important milestone in the fusion energy studies, the ITER project aims to achieve the steady combustion of the fusion reactor plasma. There are a large number of fusion products, such as neutrons and γ-rays, after the plasma fusion reactions. The measurement of fusion products is one of the most important diagnostic tasks [1,2]. In high-temperature fusion plasma, because of the inevitable impurities and high-energy ions produced from various auxiliary heating, especially neutral beam injection and ion cyclotron resonance heating, various nuclear reactions will occur. The most direct way to analyze the nuclear reactions involved is to measure the γ-ray energy spectra. By analyzing the characteristic γ-ray lines in the γ-ray energy spectra, the reaction rates of these reactions and the velocity distributions of fast ions can be obtained under certain conditions. Electron cyclotron resonance heating and deuterium neutral beam heating are main heating ways applied now in the HL-2A tokamak, the fusion plasma experimental device at the Southwestern Institute of Physics, one of the centers for fusion science, China, and the fast ions are mainly produced from the deuterium neutral beam injection and D–D fusion [3,4]. According to the discharge conditions and parameters of HL-2A tokamak, a γ-ray energy spectrum measurement system will be established. In the meantime, there are abundant neutrons produced by various nuclear reactions in plasma fusion experiments, therefore, γ-ray detection efficiency and energy resolution, signal/noise ratio and adequate neutron resistance should be considered when a γ-ray spectrometer is designed.

In JET and JT-60U [5,6], BGO and NaI detectors were used for γ-ray measurements. In our γ-ray spectrometer, a HPGe detector, which has excellent energy resolution and high detection efficiency, is used as the primary detector, and eight BGO detectors are used as anti-coincidence detectors around the primary HPGe detector, that is, they form a γ-ray Compton suppression system. Since scintillation crystals have advantages of larger volume and lower cost, scintillation crystals are considered as the anti-coincidence detector in our γ-ray spectrometer. BGO crystal is a high-Z material and has a high detection efficiency, and is relatively expensive; NaI(Tl) crystal has a poor performance for γ-ray detections; the detection efficiency of CsI(Tl) crystal is higher than that of NaI(Tl) crystal, but its luminescence decay time is longer (1000 ns) and is not suitable for high counting rates [7]; LaBr3(Ce) crystal

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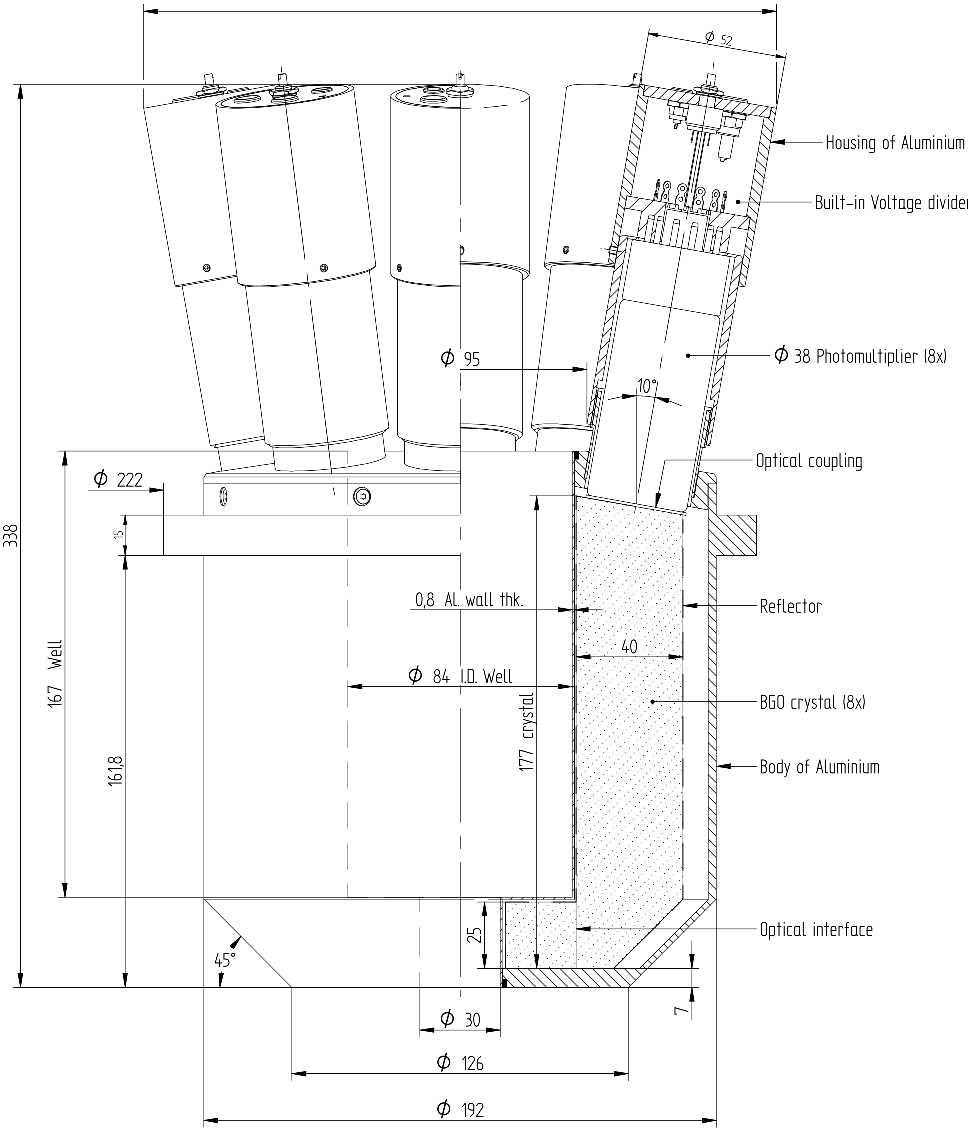

Fig. 1. The original design drawing for our Compton suppression system. The thickness of BGO hollow cylinder is 40 mm, the entrance window diameter is 30 mm and the HPGe detector diameter is 84 mm.

has much faster timing properties, with a typical decay time of 35 ns (230 ns for a NaI(Tl) crystal and 300 ns for a BGO crystal [8]), and it may have a good performance for fusion γ-ray detection, however its radiation resistance property is not so clear [7].

Our γ-ray Compton suppression system consists of a HPGe detector and eight BGO scintillation detectors as mentioned before. The original design drawing for our Compton suppression system is shown in Fig. 1 (Φ84 mm HPGe detector, 40 mm BGO hollow cylinder, Φ30 mm entrance, no BGO crystal to the back of the HPGe detector). The BGO detectors are used to absorb Compton photons escaping from the HPGe detector. If the HPGe detector and the BGO detectors simultaneously record energy deposition signals, the signals in the HPGe detector will be deleted. As a result, the Compton continuum and electron pair effect in the γ-ray spectra of HPGe detector will be suppressed, and the peak-to-Compton ratio will be improved.

Compton suppression systems for gamma-ray measurements, used for radioactive nuclide measurements for environmental samples, have been optimized by using Monte Carlo method [8]. However, to the best of our knowledge, so far there is no optimal designs for the Compton suppression system used for measurements of gamma-rays produced in tokamak experiments. The differences between the Compton suppression systems used for radioactive nuclide measurements for environmental samples and gamma-ray measurements in tokamak experiments are as follows: (1) The Compton suppression systems for radioactive nuclide measurements are usually for detecting lower energy γ-rays (generally less than 2 MeV). However, the Compton suppression systems for tokamak experiments are used to detect much wider and much higher energy range of gamma-rays, i.e., 0.1 MeV–10 MeV gamma-rays. (2) The Compton suppression systems for radioactive nuclide measurements usually have a close structure, and the radioactive samples are placed inside the system and the gamma-rays are emitted isotropically. However, the Compton suppression systems for tokamak experiments have an entrance window, and the gamma-rays impact the Compton suppression system straight through the entrance window. (3) In addition, the Compton suppression systems for radioactive nuclide measurements in general only detect gamma-rays, however, the Compton suppression systems for tokamak experiments must take into consideration the effects of neutrons, because neutrons and gamma-rays exist simultaneously in tokamak experiments.

In this paper, Monte Carlo simulations will be employed to optimize the design of our Compton suppression system for tokamak experiments. The results presented here are helpful for Compton suppression system designs in fusion studies.