Tokamak fusion neutron spectrometer based on PXI bus Postprint

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Abstract

To achieve online real-time measurement of the dynamic and time-sharing neutron spectrum of HL-2A, a tokamak fusion neutron spectrometer based on the PXI bus was developed. The system comprises an electronic system and eight thermal neutron detectors—specifically, SP9 3He proportional counters—embedded within eight polyethylene spheres of different diameters. The response function of the eight polyethylene spheres was critical for accurate calculation of the neutron spectrum. In this paper, the response function of the eight polyethylene spheres is simulated using Geant4 code, and neutron counts from a 241Am-Be neutron source are measured by the eight detectors. The calculated spectrum of the Am-Be neutron source demonstrates accuracy in the 0–2 MeV region and shows good agreement with the theoretical spectrum. The tokamak fusion neutron spectrometer was deployed on the HL-2A device to monitor the dynamic neutron spectrum of HL-2A online and in real time.

Full Text

Preamble

Tokamak Fusion Neutron Spectrometer Based on PXI Bus

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Abstract

To enable online real-time measurement of the dynamic, time-sharing neutron spectrum on HL-2A, a tokamak fusion neutron spectrometer based on the PXI bus was developed. The system comprises an electronics system and eight thermal neutron detectors—SP9 ^{3}He proportional counters—each embedded in polyethylene spheres of different diameters. Accurate neutron spectrum calculation depends critically on the response functions of these eight polyethylene spheres. This paper presents the Geant4 simulation of these response functions and measurements of neutron counts from a ^{241}Am-Be neutron source. The calculated Am-Be neutron spectrum shows good accuracy in the 0–2 MeV region and agrees well with the theoretical spectrum. The tokamak fusion neutron spectrometer has been deployed on the HL-2A device to monitor the dynamic neutron spectrum online and in real time.

Keywords: HL-2A, Response function, Calibration, Dynamic time-sharing energy spectrum, ^{241}Am-Be
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Introduction

HL-2A [1, 2] is a tokamak fusion experimental device in China that provides a foundation for advanced tokamak physics experiments and research supporting ITER and future fusion reactors. One of the major challenges in HL-2A operations is the online, real-time measurement of dynamic, time-sharing fusion neutron spectra. To address this need, we developed a tokamak fusion neutron spectrometer based on the PXI bus, consisting of an electronics system and eight thermal neutron detectors (SP9 ^{3}He proportional counters) embedded in polyethylene (PE) spheres of varying diameters. The spectrometer uploads eight time-sharing neutron counts to the PXI chassis system controller via the PXI bus. Ultimately, both the detectors and electronics will be activated by neutrons in the fusion reactor environment.

The ^{241}Am-Be neutron source serves as a common laboratory calibration standard, offering advantages of compact size, long-term stability, simple shielding requirements, and consistent neutron emission. Its activity at any given time can be calculated accurately based on radionuclide half-lives. Measuring the spectrum of an Am-Be source provides verification of the tokamak fusion neutron spectrometer without subjecting the detectors and electronics to activation by fusion neutrons. Accurate neutron spectrum calculation requires precise knowledge of the polyethylene spheres' response functions, which we simulate using Geant4 code in this work.

Principle of Measurement

The eight PE sphere spectrometers have outer diameters of 4, 5, 6, 7, 8, 9, 10, and 12 inches, respectively, with a 33-mm outer diameter SP9 ^{3}He proportional counter located at the center of each sphere. These counters are commonly used for thermal neutron measurements due to their large reaction cross sections [3] and low gamma sensitivity.

The measurement principle can be expressed mathematically as follows. Let m represent the number of PE spheres with different diameters, $R\ (E)$ the response function of the ith sphere [4, 5], $\Phi(E)$ the neutron fluence at different energies, and N_1, ⋯, N the counts recorded by the PE spheres. The ith sphere yields:

$$N_i = \int \Phi(E) R_i(E) dE$$

Neutron spectrum measurement thus reduces to solving the linear equation $R(E)\Phi(E) = N$, where $R(E)$ is the coefficient matrix derived from response functions, N represents the eight measurement data points, and $\Phi(E)$ is the neutron spectrum. While N can be obtained experimentally, the response function $R\ (E)$ must be determined through Geant4 simulation, making response function simulation critical for accurate Am-Be neutron source spectrum calculation.

A block diagram of the PXI bus-based fusion neutron spectrometer is shown in Fig. 1 [Figure 1: see original paper]. The system comprises eight detector/pre-amplifier/main-amplifier channels and a PXI chassis system controller. The charge-sensitive pre-amplifiers use NIM chassis, while the main electronics employ PXI chassis. Detector signals are amplified by the pre-amplifier, then shaped and filtered by the main electronics. DACs output upper and lower thresholds to comparators through an FPGA, which processes the comparison results between the main amplifier output and the thresholds. The FPGA uploads eight time-sharing neutron counts to the PXI chassis system controller, which calculates and displays the real-time neutron spectrum. By measuring counts from the eight PE spheres and applying the simulated response function through Eq. (2), the Am-Be neutron source spectrum can be determined.

Geant4 Simulation

The Geant4 simulation of the response function is illustrated schematically in Fig. 2 [Figure 2: see original paper] [6–8], showing eight PE spheres of different diameters (colored yellow) with the neutron source at the center. The red dots represent the eight embedded SP9 ^{3}He proportional counters, positioned 40 cm from the neutron source. Neutrons are emitted isotropically (4π solid angle) in the simulation.

Fast neutrons are thermalized through elastic collisions with hydrogen and carbon atoms in the polyethylene. For small-diameter PE spheres, low-energy neutrons have a high probability of reaching the central detector, while high-energy neutrons are likely to escape after moderation. Conversely, large-diameter spheres absorb many low-energy neutrons during moderation, but thermal neutrons slowed down from high energies can still reach the detector. This differential moderation across sphere diameters produces distinct response characteristics.

The simulated response functions are shown in Fig. 3 [Figure 3: see original paper]. Smaller spheres (e.g., 4 inches) exhibit response peaks in the low-energy region, but the peak shifts toward higher energies as sphere diameter increases. The effects of neutron escape from small spheres and scattering from the floor must be considered in the analysis.

Experimental Measurement

An experiment was designed to calibrate [9] the Geant4-simulated response functions and verify the tokamak fusion neutron spectrometer using a ^{241}Am-Be neutron source [10, 11]. The eight PE spheres were positioned as shown in Fig. 4 [Figure 4: see original paper], consistent with the simulation geometry. The fusion neutron spectrometer identifies neutron signals based on pulse amplitude, counting a signal as a neutron only when its amplitude falls between the lower and upper thresholds, as described in Section II.

Electronic noise is always present in any measurement system. To minimize its influence, the lower threshold must be set above the majority of noise pulses. Background counts were measured without the neutron source at lower thresholds of 100 mV, 120 mV, 140 mV, and 160 mV, as shown in Fig. 5 [Figure 5: see original paper]. Background counts become negligible at thresholds of 140 mV and above, so a lower threshold of 140 mV was adopted for neutron source measurements.

With lower and upper thresholds set to 140 mV and 500 mV, respectively, the count rate from the 9-inch PE sphere detecting the ^{241}Am-Be source is shown in Fig. 6 [Figure 6: see original paper]. The time-sharing counts measured for the 4, 5, 6, 7, 8, 9, 10, and 12-inch PE spheres were $N = 534$, 1077, 1161, 1717, 1768, 2367, 1959, and 662, respectively. Combining these measured data with the simulated response functions, the Am-Be neutron source spectrum was calculated using Eq. (2) and is presented in Fig. 7 [Figure 7: see original paper]. The black squares represent theoretical results from Ref. [12], while the red dots show the spectrum calculated from the response functions and measured data.

The calculated Am-Be neutron spectrum demonstrates good accuracy in the 0–2 MeV region, though relative errors increase at higher energies due to neutron scattering from the floor. Overall, the calculated spectrum shows good agreement with the theoretical spectrum, confirming that Geant4 can reliably simulate response functions for the tokamak fusion neutron spectrometer to monitor dynamic, time-sharing neutron energy spectra online and in real time.

Conclusion

A fusion neutron spectrometer with eight time-sharing neutron counters connected via PXI bus to a system controller has been developed for monitoring tokamak fusion neutron spectra. Response functions for the eight PE spheres were simulated using Geant4 software. Experimental verification using a ^{241}Am-Be neutron source demonstrated that the calculated Am-Be neutron spectrum is accurate in the 0–2 MeV region and consistent with theoretical predictions. These results validate the Geant4-simulated response functions and the tokamak fusion neutron spectrometer, which has been successfully deployed on the HL-2A device for online, real-time monitoring of dynamic neutron spectra.

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Note: Figure translations are in progress. See original paper for figures.