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D-D Fusion Neutron Spectrometer in KSTAR Tokamak

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1. Introduction

Neutron spectrometry is an essential diagnostic tool in fusion research, offering critical insights into fusion reaction rates, plasma heating mechanisms, and neutron transport dynamics. In deuterium-deuterium (D-D) fusion reactions, neutrons with characteristic energies around 2.45 MeV are emitted, providing a direct measure of plasma performance. Precise neutron diagnostics allow researchers to evaluate plasma confinement, fusion reaction efficiency, and overall tokamak performance.

The KSTAR tokamak offers an advanced experimental platform for fusion plasma research. Robust neutron diagnostics are essential for monitoring neutron emissions, analyzing plasma behavior, and optimizing operational parameters. However, neutron spectrometry in a tokamak environment is challenged by several factors:

- High-energy gamma radiation interference, which can affect neutron detection accuracy.
- Strong electromagnetic fields, which may introduce noise into measurement systems.
- High neutron flux conditions, requiring detectors with high radiation tolerance and fast response times.

To overcome these challenges, we deployed a single-crystal chemical vapor deposition (CVD) diamond-based fast neutron spectrometer within KSTAR. The intrinsic properties of diamond such as exceptional radiation resistance, superior energy resolution, and excellent neutron-gamma discrimination capabilities make it highly suitable for neutron diagnostics in fusion research. In this study, we evaluate the performance of this diamond spectrometer, compare its results to traditional neutron detectors, and discuss its potential applications in future tokamaks, including ITER and K-DEMO.

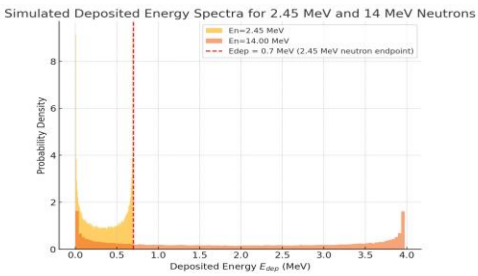
2. Experimental Setup

The experimental neutron diagnostics for the KSTAR tokamak involved a single-crystal CVD diamond fast neutron spectrometer, selected specifically for its high radiation tolerance, rapid response time, and outstanding energy resolution. The spectrometer utilizes the neutron-carbon elastic scattering reaction $^{12}C(n, \alpha)^{9}Be$ to measure neutron energies.

To characterize the detector response, GEANT4 Monte Carlo simulations were performed to compute deposited energy spectra for 2.45 MeV and 14 MeV neutrons. Specifically, the deposited energy E_{dep} in the detector is determined by neutron kinetic energy (E_n) and the carbon recoil angle (θ_R) according to the elastic scattering kinematic relation:

$$E_{dep}=0.284\times E_n\times\cos^2(\theta_R))$$

The finite energy resolution of the diamond detector system broadens the spectral features, particularly the characteristic shoulder at the maximum transferable energy ($0.284 \times E_n$). The shape of the response functions is mainly influenced by the angular distribution of the differential elastic scattering cross-section $d\sigma/d\Omega(\cos\theta_{c.m.})$. Multi-scattering events, contributing at approximately the 1% level, appear primarily as a low-energy tail beyond the main shoulder region.



Calculated deposited energy spectra from GEANT4 Monte Carlo simulation code for 2.45 MeV and 14 MeV neutrons in the diamond detector.

The employed diamond detector consisted of a single-crystal CVD diamond sensor with dimensions of 4.5 mm × 4.5 mm and a thickness of 50 μm, featuring an active detection area of 4.0 mm × 4.0 mm. The sensor was operated at a nominal bias voltage of 400 V. Comparative neutron measurements were simultaneously performed using established detectors such as He^3 counters and fission chambers for validation purposes.

High-speed electronic systems were implemented for effective signal amplification, digitization, and real-time data processing.

Experiments were conducted under varying plasma conditions, including different plasma densities, electron temperatures, and ion temperatures. Key plasma parameters—such as ion temperature (T_i), electron temperature (T_e), and plasma density (n_p)—were continuously recorded during plasma discharges. These parameters were correlated with measured neutron spectra to explore relationships between neutron emission characteristics and plasma conditions.

3. Analysis and Results

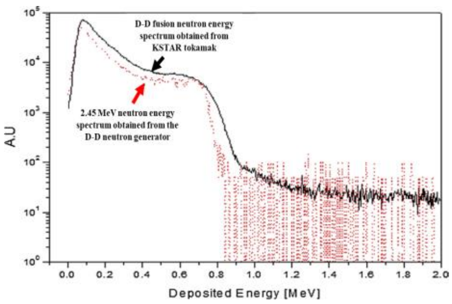
The diamond-based fast neutron spectrometer successfully measured 2.45 MeV fusion neutrons in the KSTAR Tokamak.

-Neutron Spectra Measurement: The diamond spectrometer demonstrated accurate neutron energy detection, confirming its reliability for high-energy neutron diagnostics.

-Real-Time Monitoring: The fast response time allowed time-resolved plasma diagnostics, providing insights into neutron production dynamics.

-Comparison with Other Detectors: Measurements were validated against He^3 counters and fission chambers, confirming the diamond detector's high accuracy and stability.

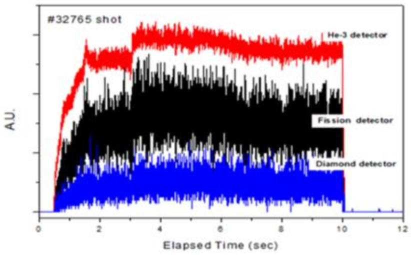
A comparative analysis of neutron energy spectra obtained from KSTAR plasma and a compact D-D neutron generator further demonstrated the spectrometer's precision.



Comparison of D-D fusion neutron energy spectra obtained from the KSTAR D-D plasma and the D-D compact neutron generator.

The results showed that neutron spectral broadening in KSTAR is independent of ion temperature and plasma density but is primarily influenced by inelastic scattering in carbon. For 2.45 MeV neutrons, the deposited energy distribution peaks around the expected maximum transferred energy ($0.284 \times 2.45 \approx 0.7$ MeV). The finite energy resolution broadens this shoulder, and a minor tail extends beyond 0.7 MeV due to multiple scattering (~1% contribution).

Additionally, neutron emission rates for a selected plasma discharge (shot #32765) were analyzed using He^3 counters, fission chambers, and the diamond spectrometer. The results demonstrated the effectiveness of diamond-based neutron spectrometry in high-radiation environments.



Comparison of neutron emission rates of shot #32765 with He^3 counters, Fission chambers, and Diamond-based fast neutron detector

The successful deployment of the diamond-based spectrometer in KSTAR underscores its potential applications in future fusion reactors such as ITER and K-DEMO. As fusion research advances, high-precision neutron diagnostics will be essential for plasma control, neutron transport analysis, and fusion performance optimization.

4. Conclusions

The CVD diamond-based fast neutron spectrometer proved to be an effective diagnostic tool for measuring D-D fusion neutron spectra in KSTAR. The spectrometer provided precise neutron energy measurements, with superior energy resolution and neutron-gamma discrimination compared to conventional detectors. Comparative validation with ^3He counters and fission chambers confirmed its accuracy and reliability in fusion plasma diagnostics. Real-time neutron detection capability allows for dynamic plasma behavior analysis. The successful deployment of this technology in KSTAR demonstrates its potential for application in next-generation fusion reactors, including ITER and K-DEMO.

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