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D-D Fusion Neutron Spectrometer in the KSTAR Tokamak

Youngseok Lee*, Jinseok Ko, Yong-Un Nam, and Hee-Soo Kim

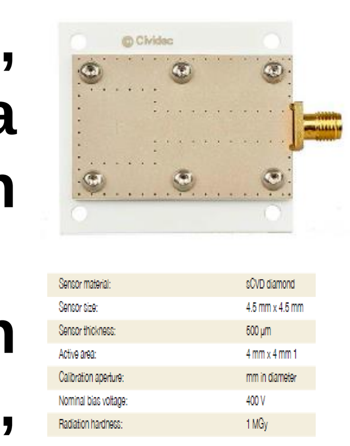
KSTAR Research Center, Korea Institute of Fusion Energy (KFE), 34133 Daejeon, Republic of Korea

**Corresponding author: yslee@kfe.re.kr*

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.

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.

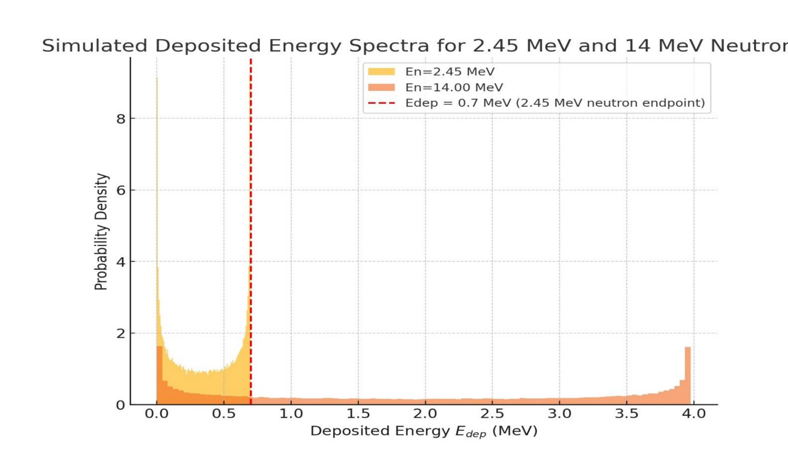


Experimental Setup

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.

The energy response spectra of the diamond detector shows the characteristic shoulder and scattering continuum due to the ^{12}C (n, el) $^{12}C^*$ reaction and the scattering recoil on ^{12}C for each neutron energy in the diamond detector. The energy released into the detector, E_{dep} depends on the incoming neutron kinetic energy (E_n) and on the ^{12}C recoiling angle (θ_R) in the laboratory coordinate system based on the elastic scattering law $E_{dep} = 0.284 \times E_n \cos^2 \theta_R$.

Neutron signals from the diamond based detector are sent to a fast-charge preamplifier, an ultra-low noise charge amplifier, and finally a data acquisition and processing system. The spectroscopic amplifier used in the work has a rise time of 80 ns, and pulse width at FWHM of 180 ns as an ultralow-noise charge amplifier.



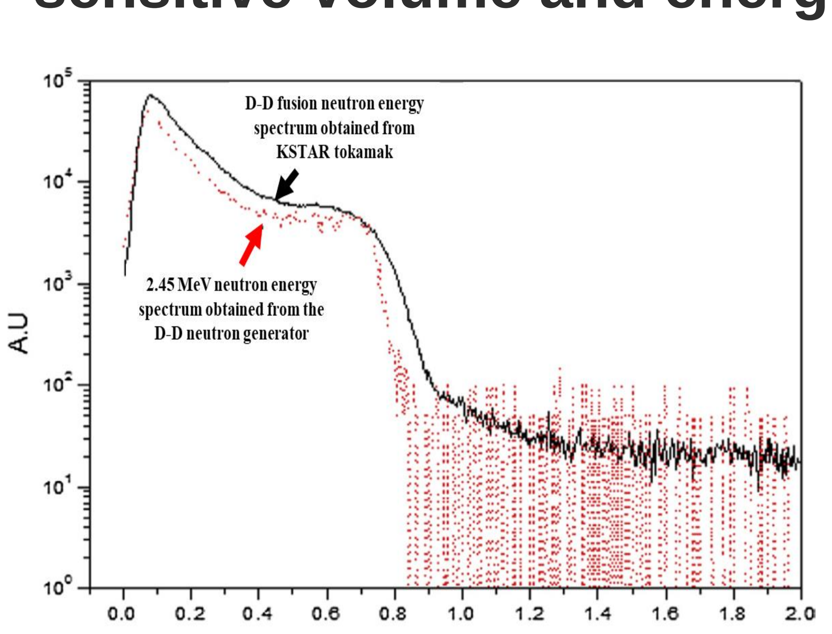
Calculated deposited energy spectra from GEANT4 Monte Carlo simulation code for 2.45 MeV and 14 MeV neutrons in the diamond detector.

Measurements of D-D fusion neutron energy and neutron emission rate

They are detected directly through the ^{12}C (n, a) ^{9}Be, ^{12}C (n, n') 3a, ^{12}C (n, d) ^{11}B , and ^{12}C (n, el) $^{12}C^*$ reactions [3]. The first three reactions have energy thresholds for incident neutrons of 6.17 MeV, 7 MeV, and 13.8 MeV respectively. The other reaction only gives rise to neutrons with energy lower than 6 MeV. In the case of a neutron energy of 2.45 MeV, the neutrons can mainly undergo elastic scattering in the ^{12}C (n, el) $^{12}C^*$ reaction.

As a result, the D-D fusion neutron energy of 2.45 MeV on KSTAR was compared to the position of the maximum edge from the energy spectrum measured with the monochromatic 2.45 MeV neutron generator.

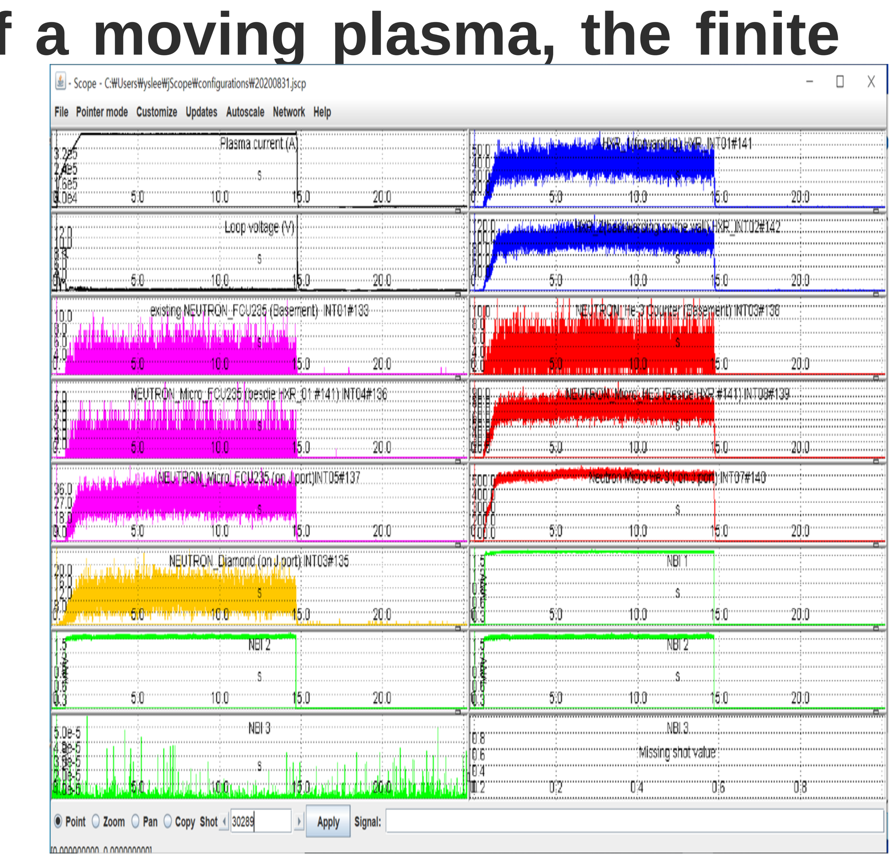
The broadening of the edge of the D-D fusion energy spectrum is due to the Doppler effects of a moving plasma, the finite sensitive volume and energy resolution of the diamond detector used.



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

The scattering continuum in the energy ranges above 0.7 MeV might be due to interactions with the 14.1 MeV neutrons of the D-T fusion reaction resulting from the burn up of fusion-produced tritons (on the order of 1 %) in the D-D plasma. The tritons are produced via the D + D → p + triton reaction with 50 % branching ratios.

Neutron emission rates for a selected plasma were analyzed using He³ 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 with He³ counters, Fission chambers, and Diamond-based fast neutron detector

Conclusions & Summary

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.